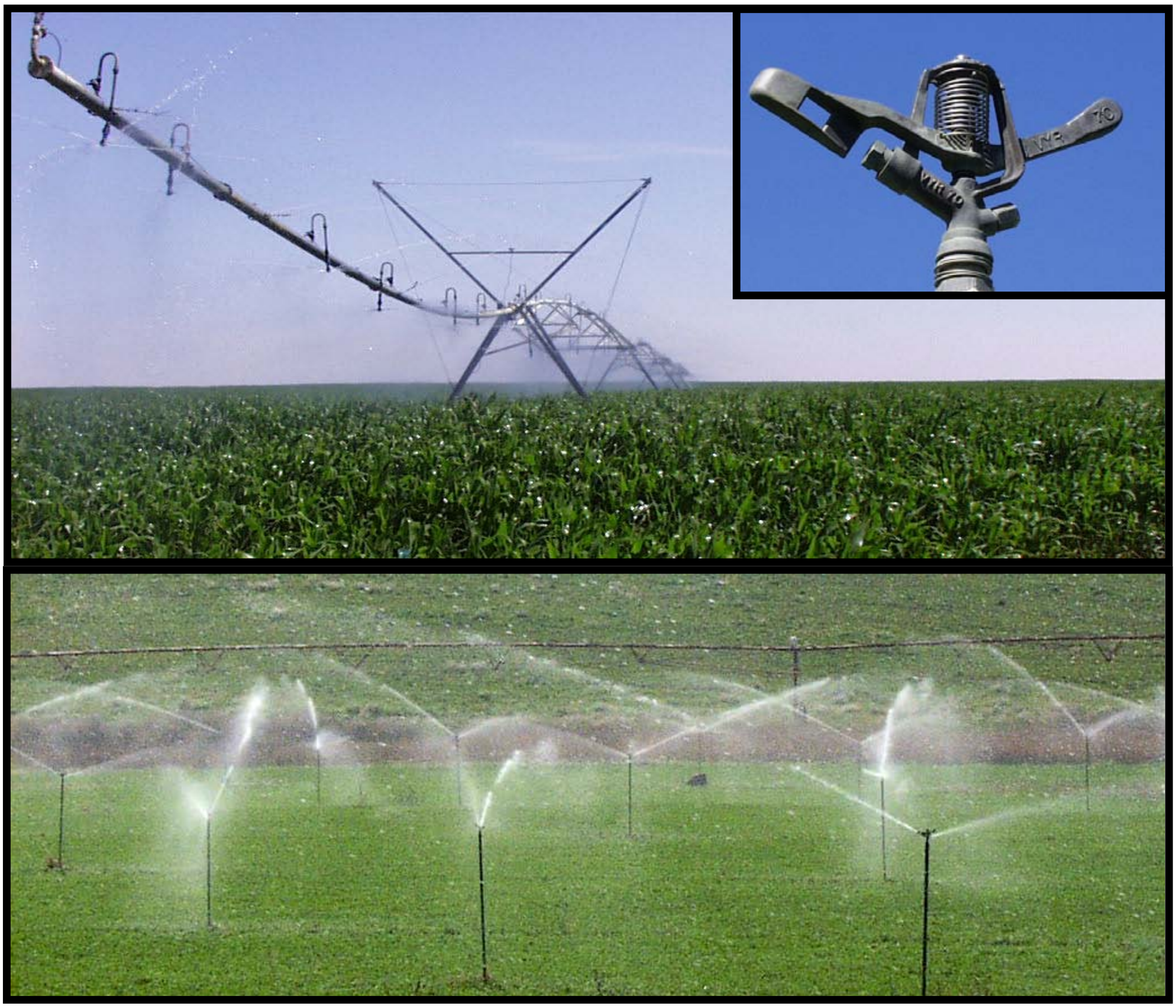
Tesis doctoral

“Contribución al estudio del riego presurizado en el valle del Ebro: del aspersor a la parcela”



Autora: **Raquel Salvador Esteban**

Dirigida por: **Dr. Enrique Playán Jubillar**

Universidad de Zaragoza
Departamento de Agricultura y Economía Agraria

Tesis doctoral

Contribución al estudio del riego presurizado en el valle del Ebro: del aspersor a la parcela

Autora: **Raquel Salvador Esteban**

Dirigida por: **Dr. Enrique Playán Jubillar**

Universidad de Zaragoza. Departamento de Agricultura y Economía Agraria

Programa: Avances en Ciencias Agrarias y del Medio Natural

2011

AGRADECIMIENTOS

A Miguel, Damián y Lázaro que han vivido conmigo todo este proceso con mucha paciencia y dándome ánimos cuando los he necesitado.

A mi director de tesis Enrique Playán por hacerme la vida muy fácil, su apoyo, ideas y consejos. Gracias por todo, imposible encontrar un director mejor.

A mis padres, que siempre han creído en mí y han estado allí cuando les he necesitado.

A mis compañeros durante estos cuatro años. Me llevo buenos amigos, grandes charlas y muchas risas. Gracias por todo a Piluca, Cristina, Nery, Begoña, Bilel, Samuel, Kosana, Yeny, Raquel A., Borja, Ilyes, Elena, Raquel R y Hamed.

Gracias a todos los investigadores del grupo y al personal de suelos y riegos que me han ayudado y escuchado en todo momento.

A las chicas por sus consejos y buenos ratos, gracias.

RESUMEN

La superficie regada en la cuenca del Ebro es de 783.948 ha, lo que representa más de la quinta parte de los regadíos de España. Un manejo eficiente del agua de riego repercute tanto en la cantidad como en la calidad del agua disponible en la zona. Dentro de la cuenca del Ebro los sistemas de riego agrícolas son muy variados, aunque la tendencia actual es de aumentar la superficie regada por sistemas presurizados, resultando muy importante el estudio en detalle de estos sistemas de riego. En general, en la cuenca del Ebro predominan los cultivos extensivos de verano, aunque en algunas zonas resultan muy importantes los cultivos hortícolas, los frutales o la viña. En el estudio de los diversos usos del agua en la cuenca del Ebro, hay que tener en cuenta también la importancia del riego de jardines, ya que la superficie ajardinada tanto pública como privada está creciendo rápidamente en los últimos años. Además, en la mayor parte de los jardines privados en España, el agua utilizada para el riego es agua potable, representando este hecho un problema tanto económico como medioambiental.

Los objetivos de esta tesis pretenden aumentar los conocimientos actuales sobre el riego presurizado, tanto desde una visión en detalle del mismo como desde una perspectiva de adecuación del riego a las necesidades de las plantas. Así, se pretende desarrollar y validar un método fotográfico para la caracterización de las gotas en el riego por aspersión. También se pretende analizar la influencia de diversos factores en la toma de decisiones en riego presurizado mediante el análisis de la base de datos de un sistema de telecontrol. Igualmente, se pretende analizar la evolución temporal y la calidad de riego en jardines urbanos privados mediante un caso de estudio en la ciudad de Zaragoza. El último objetivo es determinar la calidad estacional del riego agrícola en parcela en la cuenca del Ebro, analizando la influencia del cultivo y del sistema de riego.

En este trabajo se han utilizado una amplia gama de metodologías. Para la caracterización de las gotas por un aspersor agrícola se adaptaron técnicas fotográficas y se utilizaron programas de tratamiento de imágenes. Para el estudio de la programación y adecuación del riego presurizado en los distintos contextos, fueron aplicadas diversas técnicas estadísticas y de minería de datos con el objeto de obtener y analizar la información necesaria.

La técnica fotográfica aplicada para la caracterización de las gotas de un aspersor agrícola sirvió para caracterizar un total de 1.464 gotas a distancias del aspersor desde 1,5 a 12,5 m. Además, resultó factible la caracterización por separado de las gotas emitidas por la boquilla principal y por la pala del aspersor en algunas de estas distancias.

En el estudio de la programación en parcelas con riego presurizado se analizó la evolución temporal de las programaciones de riego a lo largo de cinco campañas. El número de hidrantes regando en cada momento se vió influenciado por la meteorología. Se ejecutaron análisis estadísticos con los que pudieron clasificar los patrones de programación de riego de los hidrantes en diez grupos diferentes, siendo la variable más influyente en esta clasificación el usuario del agua en cada hidrante y año.

La adecuación del riego de los jardines privados a las necesidades hídricas de las plantas resultó escasa, siendo común el sobrerriego, sobre todo en otoño. De hecho, el promedio de la altura de agua aplicada (1.359 mm) resultó ser mucho mayor que las necesidades hídricas calculadas (555 mm). Sólo en el 34 % de los jardines el riego resultó adecuado, siendo un 60 % el número de jardines en los que el sobrerriego estaba presente.

La adecuación del riego en parcelas agrícolas de la cuenca de Ebro fue mejor que la del riego urbano. Los datos promedio obtenidos sugieren un ligero estrés hídrico. Se detectaron diferencias entre sistemas de riego y entre combinaciones de sistema de riego y cultivo. Se estudió la productividad de varios cultivos, resultando los menos productivos el arroz y girasol. Los frutales se encontraron entre los cultivos más productivos.

Entre las conclusiones obtenidas en este trabajo se inclyue que la técnica de caracterización de gotas del aspersor aislado proporcionó datos de gran calidad, aunque la ejecución de las mediciones resultó muy laboriosa. Además, el estudio de la programción de riego presurizado sugirió que los regantes no tienen la capacidad suficiente como para desarrollar patrones de riego consistentes y específicos para cada sistema de riego y cultivo. En cuanto a la adecuación del riego en jardines, resultó bastante pobre, probablemente debido al bajo coste relativo del agua de riego y a los elevados ingresos familiares medios de la zona de estudio. La adecuación del riego en parcelas agrícolas resultó ser mejor, permitiendo concluir que los agricultores de la zona riegan con cautela obteniendo razonables producciones.

ÍNDICE GENERAL

1. INTRODUCCIÓN GENERAL

1. INTRODUCCIÓN GENERAL

El riego agrícola y urbano en el valle del Ebro

La cuenca del Ebro se encuentra en el Noreste de España y tiene una superficie de 85.362 km^2, de los cuales 84.415 km^2 se encuentran en España y el resto entre Francia y Andorra. El clima en la zona es mediterráneo continentalizado, localizándose los periodos más frecuentes de sequía en invierno y final de otoño. La precipitación media en la cuenca es de 622 mm/año y su distribución espacial presenta valores máximos en las zonas montañosas del norte y mínimos en el sector central por donde discurre el río Ebro.

La cuenca del Ebro proporciona agua de riego a un total de 783.948 ha, la mitad de las cuales se encuentran en Aragón. Esta superficie regada representa más de la quinta parte de los regadíos de España. Los cultivos que tradicionalmente se encuentran en la cuenca del Ebro dependen en gran medida de la localización geográfica que se estudie en cada momento. Así, en la provincia de Zaragoza y también algunas comarcas de Huesca, Navarra, y Teruel predominan los cultivos extensivos, con especial énfasis en el maíz y la alfalfa. Los frutales son importantes en algunas zonas de Aragón (vegas del río Jalón, las zonas de la provincia de Huesca limítrofes con Lérida y en el Bajo Aragón) y en Cataluña. En el alto Ebro predominan los cultivos hortícolas, sobre todo en las provincias de La Rioja, Álava y Navarra (Pinilla, 2002).

Dentro de la cuenca del Ebro, los sistemas de riego en parcela son muy variados (Confederación Hidrográfica del Ebro, 2008), siendo el sistema mayoritario el riego por gravedad (69 % de la superficie regada) seguido por el riego por aspersión (19 %) y, por último, el riego por goteo (12 %). Actualmente, la tendencia es que disminuya la extensión de los cultivos regados por gravedad y que aumente la extensión de los sistemas de riego presurizados.

En la mayor parte de los jardines privados en España, el agua utilizada para el riego es agua potable, representando este hecho un problema tanto económico como medioambiental. Esto se debe a que se están invirtiendo recursos en tratar un elevado volumen de agua que es utilizado en usos que no requieren ese nivel de calidad.

En el valle del Ebro (como en el resto de España), el riego de jardines privados se ha incrementado considerablemente en los últimos años, debido al auge de las urbanizaciones con viviendas unifamiliares con jardín. Aunque a finales del siglo XX sólo un 5 % de las viviendas en Zaragoza tenían jardines privados (Ayuntamiento de Zaragoza, 1999), este porcentaje ha aumentado considerablemente en los últimos años debido a la creación de nuevas zonas de viviendas en las que predomina la expansión horizontal. En estas nuevas zonas urbanas se estima que el porcentaje del agua total que se utiliza en el riego de jardines es del 56 % (Loh y Coghlan, 2003).

Caracterización del riego por aspersión

La caracterización de gotas en el riego por aspersión tiene numerosos propósitos, entre ellos estudiar las pérdidas por evaporación y arrastre, analizar el impacto de las gotas sobre la superficie del suelo y simular la aplicación del agua de riego con el objeto de estimar de valores de eficiencia y uniformidad. Cuando se habla de simulaciones del riego por aspersión, la distribución de los diámetros de gotas emitidas por un aspersor es un dato a introducir en todos los casos. Una adecuada caracterización de estos diámetros de gotas repercutirá en la calidad de la simulación obtenida en cada caso. Resulta asimismo importante la caracterización de la influencia de las distintas variables que modifican la calidad del un riego por aspersión. Estas variables pueden ser propias del sistema de riego (marco de riego, modelo de aspersión tamaño y número de boquillas, altura del aspersor…) o ambientales (velocidad del viento, temperatura y humedad relativa). Los modelos balísticos de simulación del riego por aspersión requieren toda esta información para determinar la velocidad de las gotas emitidas por un aspersor en cada evento de riego (Carrión et al., 2001; Playán et al., 2006).

Con el objeto de estimar la distribución de los diámetros de gota de la boquilla de un aspersor, se utilizan en los programas de simulación del riego por aspersión técnicas de simulación inversa (Montero et al., 2001 y Playán et al., 2006). Siguiendo estas técnicas pueden identificarse parámetros de distribución de gotas que reproduzcan patrones observados anteriormente en ensayos de campo. Sin embargo, si se dispusiera de datos de gotas medidos “in situ”, sería más sencillo poder calibrar estos modelos de simulación y por lo tanto aumentar tanto la calidad como la cantidad de dichas simulaciones.

Diversos trabajos han descrito diferentes técnicas de medición de gotas en distintos sistemas de aspersión. Muchas de estas técnicas comenzaron a utilizarse a finales del siglo XIX (Wiesner, 1895) y su evolución ha sido estudiada por numerosos autores (Cruvinel et al., 1996; Cruvinel et al., 1999; Salles et al., 1999; Sudheer and Panda, 2000 y Montero et al., 2003). Los métodos de medición de gotas pueden clasificarse de la siguiente manera:

- Método de la mancha (Magarvey, 1956).
- Método de la harina (Kohl y DeBoer, 1984).
- Método de inmersión en aceite (Eigel y Moore, 1983).
- Método de medición del momento (Joss y Waldvogel, 1967).
- Método fotográfico. Esta metodología se basa en la toma de fotografías de alta velocidad a las gotas procedentes de un determinado emisor. Aunque la técnica se empleó inicialmente para fotografiar gotas de lluvia (Jones, 1956), recientemente se ha utilizado para el estudio del diámetro de gotas de distintos tipos de emisores (Sudheer y Panda, 2000).
- Métodos ópticos. En la actualidad, para la medición del diámetro de gotas de diversos emisores, pueden ser utilizadas dos tipos de técnicas de medición ópticas. La primera de ellas analiza la desviación de un rayo láser al incidir sobre cada gota (Kincaid et al., 1996) y la segunda (disdrómetro óptico) mide la atenuación de un haz de luz al atravesar dichas gotas (Hauser et al., 1984 y Montero et al., 2003).

Los métodos de medición de gotas mediante técnicas ópticas proporcionan estimas automáticas del diámetro de un conjunto de gotas, siendo una ventaja de estos métodos la posibilidad de obtener un gran número de mediciones en un tiempo relativamente corto. Sin embargo, en estas metodologías existen diversas fuentes de error producidas tanto por el solapamiento de gotas como por el paso a través del haz de luz de únicamente una parte de la gota. Recientemente, Burguete et al. (2007) presentaron un método estadístico para rechazar las gotas en cuyas mediciones pudiera haber errores.

La necesidad de métodos de medición de gotas alternativos para evaluar las características del conjunto de gotas emitidas por un aspersor está motivando la búsqueda de métodos de caracterización directa tanto del diámetro de las gotas como de su velocidad y ángulo de caída. Recientes investigaciones en fotografía digital permiten obtener un análisis detallado del conjunto de gotas emitidas por un aspersor, siendo este método una alternativa interesante ya que no requiere de equipamiento específico.

Uso del agua en el riego presurizado urbano

En los países mediterráneos entre los que se incluye España, el césped es tratado como un bien posicional (Hirsch, 1976), dado que es poco frecuente encontrarlo en los paisajes naturales de la mayor parte del país. Por esta razón, es común encontrar césped como especie predominante en los jardines de las ciudades (públicos o privados), acompañado por otras especies típicas de climas atlánticos. La mayor desventaja de estas especies es su elevada necesidad de agua, que en este clima no puede ser aportada por precipitación natural y tiene, por lo tanto, que ser suministrada por medio del riego.

Las necesidades hídricas de un jardín son calculadas teniendo en cuenta diversos factores, siendo los más importantes los derivados de la climatología de la zona y de las necesidades de riego de las especies presentes en el jardín. Otros factores son la coexistencia de dos o más especies en la misma superficie de suelo y variables que modifican el clima tales como la exposición al viento. Diversos trabajos de investigación estudian las necesidades de riego de los jardines mediante uno de estos tres enfoques: La primera opción (Haley et al., 2007) es el estimar que las necesidades de riego netas del jardín son iguales al valor de la evapotranspiración de referencia (ET_0). Esta suposición resulta lógica si la mayor parte del jardín está compuesto por césped. La segunda opción se basa en la estima directa de las necesidades de riego del jardín por medio de instrumentos tales como sensores que miden la humedad del suelo (Morari y Giardini, 2001; White et al., 2004) o mediante la utilización de lisímetros de pesada (Brown et al., 2001). Por último, un grupo de autores (Domene y Saurí, 2003; Contreras et al., 2006) siguen la metodología propuesta por Costello et al. (2000), quienes desarrollaron el método WUCOLS para determinar las necesidades hídricas de los jardines. El método WUCOLS está basado en las estimaciones de ET_0, pero esta variable es transformada mediante un coeficiente llamado Coeficiente del Jardín (K_L). Este K_L sustituiría al Coeficiente de Cultivo (Kc) utilizado para el cálculo de las necesidades de riego en cultivos agrícolas.

En diversos estudios realizados en jardines privados, se ha encontrado que el exceso de riego es común en un alto número de casas, particularmente en otoño (Hunt et al., 2001; White et al., 2004 y Endter-Wada et al., 2008) y en jardines pequeños (Kjelgren et al., 2000). Esto se debe a que la programación de riego no se adapta a tiempo al pasar del verano al otoño, periodo en el cual las necesidades de riego de los jardines disminuyen notablemente.

La calidad del riego es un tema tratado por numerosos autores tanto en jardines públicos como privados. En estos trabajos se relaciona la calidad del riego con numerosos factores tales como el precio del agua, el nivel de renta (tanto individual como en la zona estudiada), la carta de especies ornamentales cultivadas en el jardín, el tamaño del jardín, el sistema de riego, la presencia de programadores de riego y el nivel de información recibido por los usuarios (Hunt et al., 2001; Domene y Saurí, 2003; Syme et al., 2004; Domene y Saurí, 2006 y Parés-Franzi et al., 2006). El uso del agua en jardines se ha estudiado detalladamente en tres ciudades españolas: Barcelona (Domene y Saurí, 2003; Domene y Saurí, 2006; Parés-Franzi et al., 2006), Murcia (Contreras et al., 2006) y Madrid (Moreno et al., 2007).

Uso del agua en parcela en el riego presurizado agrícola

El uso tradicional de agua de riego implica el aporte adicional de agua a los cultivos en los periodos en los que las lluvias no son suficientes para satisfacer las necesidades del mismo o para que las plantas alcancen su máxima producción (Doorenbos y Pruitt, 1992). En la actualidad, esta máxima está cambiando, pasando a ser el riego la cantidad de agua que se aplica a los cultivos para obtener el máximo beneficio económico. Este volumen de agua de riego no siempre es el que hace que el cultivo se encuentre en las mejores condiciones y/o llegue a su máximo productivo. Así, el agua, como recurso escaso que es, necesita de una utilización más eficiente no sólo en términos biológicos sino también económicos. Por este motivo, es necesario hacer una estimación de los costes y beneficios que cada combinación de cultivo-sistema de riego-parcela producen en función de los numerosos tipos de manejo posibles (De Juan y Martín de Santa Olalla, 1993).

Todos los usuarios del agua de una cuenca hidrográfica comparten responsabilidades en cuanto a conservación del recurso, tanto en cantidad como en calidad. La evaluación de cómo se está aplicando el agua en las áreas regables de una cuenca hidrográfica y el cálculo del beneficio económico que se obtiene en cada zona y de cada cultivo es imprescindible para clasificar y plantear escenarios de mejora. Estos escenarios deben diseñarse para cada zona en concreto conociendo sus particularidades y sus índices de calidad del riego.

Existen diversos procedimientos para describir y evaluar la calidad del riego a nivel de parcela. El clásico trabajo de Merriam y Keller (1978) fue una de las primeras recopilaciones de indicadores de calidad del riego. Burt et al. (1997), presentaron diversos índices de calidad del riego, incluyendo conceptos como eficiencia de riego, coeficiente de uso consuntivo del riego y sagacidad del riego. Malano y Burton (2001) mostraron una recopilación de diversos indicadores para estimar, entre otros parámetros, la calidad del riego. Entre ellos, el índice ARIS (*Annual Relative Irrigation Supply*), destaca por la utilización para su cálculo de variables relativamente sencillas de obtener o estimar. Así, el índice ARIS se calcula como el coeficiente entre la cantidad de agua aplicada a una parcela y las necesidades de riego netas de la misma. En el valle del Ebro se han realizado algunos estudios en zonas concretas aplicando ARIS o índices similares (Faci et al., 2000; Cavero et al., 2003; Dechmi et al., 2003a; Lecina et al., 2005 y Zapata et al., 2009), aunque no se han abordado hasta este momento estudios de riego en parcela a nivel de cuenca.

Las zonas regables dentro de la cuenca del Ebro se agrupan dentro de comunidades de regantes, las cuales gestionan el recurso según sus propios estatutos. En las comunidades de regantes en las que predomina el riego presurizado es común encontrar sistemas de telecontrol que registran datos sobre el riego en cada uno de los hidrantes a la vez que participan en la apertura y cierre de las válvulas que dan entrada al agua en la parcela. Además, en casi todas las parcelas de estas comunidades de regantes se instalan programadores de riego que controlan los tiempos de riego de cada sector en los que se divide la parcela. La forma en la que cada agricultor programa los riegos en sus parcelas es un tema poco estudiado y que puede proporcionar información muy interesante a la hora de diseñar programadores de riego que se adapten a sus gustos y necesidades. No son abundantes en la literatura los artículos científicos que profundizan en el factor humano como una variable determinante en la toma de decisiones en el riego presurizado. Clemens y Dedrick (1992) analizaron varios factores (entre los que se incluye el factor humano) que afectan al uso del agua de riego en una zona de riego por superficie en Maricopa (Arizona, USA). Dechmi et al. (2003b), evaluó el efecto de diferentes variables (incluyendo las relacionadas con el agricultor) en la altura de agua final aplicada al cultivo. Merot et al. (2008) analizaron la relación entre prácticas de riego y el manejo del cultivo en una zona en la que predominaba el riego por superficie. Brown el at. (2010) diseñaron un programador-simulador que cuantifica la influencia de las decisiones tomadas por los agricultores en el riego y la producción. Otros trabajos se centraron en periodos de escasez (Fayase et al., 2003), riego con aguas residuales (Styczen et al., 2010) o fluctuaciones de precio de los productos agrícolas (Cortigniani and Severini, 2009).

2. OBJETIVOS

2. OBJETIVOS

En esta tesis doctoral se pretende aportar nuevos conocimientos al estudio del riego presurizado en el valle del Ebro. Para ello, se va a analizar desde la distribución de gotas de un aspersor hasta la adecuación del riego presurizado en parcela, tanto agrícola como en jardines privados. Además, se realiza una aproximación al estudio de la influencia de diversos factores en la toma de decisiones en cuanto a la aplicación del riego presurizado agrícola se refiere. La consecución de este objetivo general se basa, a su vez, en la consecución de los objetivos principales y secundarios que se enumeran a continucación:

1) Desarrollar y validar un método fotográfico para la caracterización de las gotas del riego por aspersión.
   a) Optimizar la combinación de color de fondo, velocidad de obturación y apertura de diafragma para la correcta medición de las gotas emitidas por el aspersor.
   b) Desarrollar una metodología de trabajo para la toma y tratamiento de imágenes de gotas emitidas por el aspersor.
   c) Validar la metodología desarrollada con mediante un ensayo en parcela con una combinación de altura de toma de imágenes, aspersor, presión de funcionamiento y tamaños de boquillas.
   d) Medir e identificar el número, tamaño, velocidad y ángulo de caída de las gotas de un aspersor agrícola a varias distancias del mismo.

2) Analizar la influencia de diversos factores en la toma de decisiones en riego presurizado mediante el análisis de la base de datos del sistema de telecontrol de la Comunidad de regantes de Candasnos (Huesca, España).
   a) Crear una base de datos de eventos de riego para riego presurizado, combinando datos de cultivo, año, hidrante, regante, agrometeorología y sistema de riego.
   b) Clasificar los patrones de riego observados en función de la información contenida en el conjunto de eventos de riego de una campaña.

c) Analizar detalladamente casos de estudio individuales. Extraer información acerca de la influencia de distintas variables en el patrón de riegos.

3) Analizar la evolución temporal y la calidad del riego en jardines urbanos privados mediante un caso de estudio en la ciudad de Zaragoza.

   a) Describir los tipos de vegetación y estimar las necesidades hídricas netas de los jardines estudiados.

   b) Analizar la variación bimensual los volúmenes de agua utilizados tanto para riego como para agua potable.

   c) Analizar la calidad del riego en los jardines urbanos privados estudiados mediante la comparación entre volumen de agua de riego aplicado y necesidades hídricas netas del jardín.

4) Determinar la calidad estacional del riego agrícola en parcela en la cuenca del Ebro, analizando la influencia del cultivo y del sistema de riego.

   a) Analizar la calidad estacional del riego agrícola en parcela en la cuenca del Ebro, poniendo especial interés en las diferencias entre cultivos y sistemas de riego.

   b) Determinar la productividad del agua de riego en los casos en los que se dispone de datos sobre el rendimiento de los cultivos y sus costes de producción.

3. SCIENTIFIC CONTEXT AND RESEARCH ISSUES

3. SCIENTIFIC CONTEXT AND RESEARCH ISSUES

3.1. Characterization of drops emmited by agricultural sprinklers

The characterization of drops resulting from impact sprinkler irrigation typically implies the determination of their diameter as they approach the soil surface. Drop characterization has been used for different purposes related to irrigation management, such as evaporation losses, soil conservation and irrigation simulation. Evaporation losses have often been correlated with wind speed (Edling, 1985; Trimer, 1987; Keller and Bliesner, 1990; Tarjuelo et al., 2000; Playán et al., 2005). Wind speed has been found to affect fine drops much more than large drops (Fukui et al., 1980; Thompson et al., 1986, De Lima et al., 1994; De Lima et al., 2002). Regarding soil conservation, drop kinetic energy results in soil surface sealing, compaction and erosion (Bedaiwy, 2008). This energy is directly related to drop diameter and velocity (Kincaid, 1996). In kinetic energy analyses of sprinkler irrigation, drop velocity was estimated using simulation models (Kincaid, 1996). When it comes to simulating sprinkler irrigation, the distribution of drop diameters is a primary input. An adequate characterization of this variable is required to estimate the differences in performance resulting from different irrigation equipments, operating conditions or changes in the environment (particularly wind speed). Ballistic sprinkler simulation models (Carrión et al., 2001; Playán et al., 2006) require this information to estimate the landing point and terminal velocity of drops resulting from a certain irrigation event. Procedures have been developed to estimate drop diameter distribution at the nozzle from the sprinkler application pattern using inverse simulation techniques (Montero et al., 2001; Playán et al., 2006). Following these techniques, drop distributions can be identified that reproduce observed application patterns.

As a consequence of these irrigation management and simulation needs, irrigation drop characterization has been a traditional field of research. Different techniques have been developed since the end of the 19th Century (Wiesner, 1895). The evolution of drop characterization techniques as related to natural or irrigation precipitation has been reported by a number of authors (Cruvinel et al., 1996; Cruvinel et al., 1999; Salles et al., 1999; Sudheer and Panda, 2000; Montero et al., 2003). A succinct discussion of the methods reported in these papers follows:

Stain method. It is based on the measurement of the stain created by a drop when impacting on an absorbing surface. Since stain and drop diameters are correlated, stain diameters can be used to estimate drop diameters (Magarvey, 1956).

Flour method. Drops impacting on a thin layer of flour create pellets whose mass or diameter is statistically related to drop diameter (Kohl and DeBoer, 1984)

Oil immersion method. Based on the fact that water droplets can get trapped in a fluid with adequate density. Drops are then observed with appropriate optical equipment to measure their diameter (Eigel and Moore, 1983)

Momentum method. Includes a variety of techniques (mostly applied to natural precipitation) based on the use of pressure transducers to estimate the kinetic properties of sets of drops (Joss and Waldvogel, 1967).

Photographic method. The methodology is based on high-speed photographs of drops in an irrigation jet. The technique first focused on photographing raindrops (Jones 1956). Recently, photographs have been used to estimate drop diameter through digital techniques (Sudheer and Panda, 2000).

Optical methods. In the last decade of the 20th Century, two types of optical methods were applied to measure drop diameter. The first one is based on the analysis of the deviation of a laser flow as it passes through drops of different characteristics (Kincaid et al., 1996). The second one, the optical disdrometer, measures the attenuation of a luminous flow (Hauser et al., 1984; Montero et al., 2003). Both methods provide automated estimates of drop diameter in a set of drops.

Optical methods count on the advantage of being fully automated in data collection, thus permitting fast, repeatable drop characterization. These methods have however specific sources of errors, such as those induced by side-passing drops and overlapping drops. Recently, (Burguete et al., 2007) presented a simulation study characterizing the relevance of these errors under a number of experimental conditions, and proposed a statistical method to reject erroneous drops. Burguete et al. (2007) theoretically analysed the use of the disdrometer to estimate drop velocity from drop time of passage, and found it subjected to large experimental errors.

The need for an alternative, simple method for evaluating the characteristics of sets of drops motivated the search for a direct drop characterization method able to provide information on at least drop diameter and velocity. Recent developments in digital photography oriented the search towards a photographic method which could be used to obtain data sets adequate for detail analysis of sprinkler irrigation problems. Such a method stands as an attractive alternative, since it does not require specific equipment.

3.2. Irrigation scheduling in pressurized networks: the human factor

On-farm irrigation scheduling is an important topic of study at two different levels. At the farm level, irrigation scheduling will determine crop yield in both quantity and quality. At the collective level, the addition of the irrigation flows demanded by all hydrants of an irrigation network (resulting from farmer's irrigation scheduling), will determine the network demand and operating conditions throughout the irrigation season.

Designing an on-farm irrigation schedule in a pressurized irrigation system implies selecting the timing and duration (depth) of the irrigation events (Clemmens, 1987). An additional constrain is the search for maximum efficiency and uniformity in each irrigation event. The irrigation system design determines a maximum value of both efficiency and uniformity in each plot. Reaching these maximum values in each irrigation event will depend on the adequate selection of irrigation time and duration. These variables are selected at the beginning of the irrigation, although they can be modified during the irrigation event. In the case of sprinkler irrigation, the environmental conditions (subjected to relevant inter- and intra-day variability) will strongly determine irrigation uniformity and the percentage of wind drift and evaporation losses. Selecting the most adequate irrigation time and duration will minimize the effect of environmental conditions on sprinkler irrigation quality (Playán et al., 2005) and will maximize irrigation efficiency and/or crop yield.

Collective pressurized irrigation networks are designed to meet certain simultaneity, characterized by the number of open hydrants in each network segment (Lamaddalena and Sagardoy, 2000). During network operation, the time evolution of the number of open hydrants is determined by the physical design of the on-farm irrigation systems, crop water requirements, energy costs and the Water Users Association (WUA) organizational rules. However, the approach of individual farmers to on-farm irrigation scheduling very strongly determines hydrant operation, and can provide interesting information for the optimization of irrigation network design and maintenance.

The design of collective pressurized irrigation networks poses relevant constraints to farmer irrigation scheduling in some areas. Some of these limitations derive from the flow limiting valves. This determines the maximum number of sprinklers or drippers which can irrigate at the same time or the pivot size. The maximum hydrant discharge also determines the maximum crop water requirements that can be met, and may result in continuous irrigation operation during the period of peak crop water requirements, regardless of the intraday and interday changes in environmental conditions or energy costs. Other limitations derive from the organizational rules adopted by the WUAs. Rigid schedules deriving from the planning of pumping stations or energy use can result in severe limitations to farmers' capacity to respond to crop water requirements. On-farm irrigation controllers have been designed to implement farmers' scheduling decisions. However, on-farm controllers have also been reported to complicate the implementation of optimum irrigation scheduling (Zapata et al., 2009). Users should master their advanced irrigation controllers in order to implement all features leading to scheduling flexibility. This flexibility is required to adapt to changing environmental and water resources conditions. Most of the agricultural irrigation controllers in the market have very limited possibilities in this respect, and have been designed to produce rigid irrigation schedules

If the characteristics of the collective pressurized irrigation network, the on-farm irrigation system and the controller are important for an adequate irrigation schedule, the human factor stands as the most decisive factor. It is the farmer who judges the available information and produces the schedule leading to an irrigation event. The farmer may also decide to interrupt irrigation when agrometeorological conditions are not are adequate for the irrigation system. In order to make these decisions, a farmer in a country such as Spain can count on several information sources. Web pages have been created which publish current irrigation requirements for the most common crops in a region (Department of

WaterResources, 2011; Government of Aragón, 2011). Additionally, continuous education programs are available to farmers, particularly in lrge irrigation projects. As a consequence, most professional farmers are aware of the relevance of agrometeorological conditions on irrigation scheduling (regarding crop water requirements and the effect on sprinkler irrigation efficiency). This is particularly important in areas characterized by strong winds, since wind speed is the agrometeorological factor most limiting sprinkler irrigation performance (Tarjuelo et al., 1999; Zapata et al., 2007; Sanchez et al., 2010). In drip irrigation, farmers' scheduling decisions are not so directly influenced by the environment, and often respond to fertigation requirements and regulated deficit irrigation policies, in addition to crop water requirements.

Scientific research focusing on the importance of the human factor on irrigation decision making is not abundant in the literature. Clemmens and Dedrick (1992) analyzed the factors (including human factors) affecting farm water use in the surface-irrigated area of Maricopa (Arizona, USA). Dechmi et al. (2003b) evaluated the effect of different variables (including those related to the farmer) on the final irrigation depth and crop yield. Merot et al. (2008) studied the relationship between irrigation practices and crop management in a surface-irrigated area. Brown et al. (2010) predicted the influence of farmers' irrigation decisions on the final crop yield. Research about the influence of human factors on decision making about cropping patterns is more common in the literature. These studies have focused on issues such as water scarcity (Faysse, 2003), wastewater irrigation (Styczen et al., 2010), or fluctuations in the price of agricultural commodities (Cortignani and Severini, 2009).

Detailed on-farm irrigation schedules in pressurized irrigation have not been the target of recent research efforts. Scientific activities have been often oriented to simulating and/or recommending irrigation schedules (Cancela et al., 2006; Liyuan et al., 201X). Other studies have focused on monitoring on-farm irrigation, and analyzed data to propose irrigation calendars (Chopart et al., 2007). Detailed studies of farmer irrigation scheduling can be used to elucidate current trends in on-farm pressurized irrigation. Results will be used by researchers (as a source for insight and a source of validation data for irrigation decision making models) and by irrigation engineers (as feedback to improve their designs). As a consequence, assessing the factors guiding farmers' irrigation scheduling will lead to more water- and cost-effective future pressurized collective irrigation networks.

Remote surveillance and control systems (RSCS) are being installed in many new irrigation networks in Spain. These systems can provide valuable information on individual farmers' irrigation schedules. As a consequence, RSCS can not only provide a service to the farmers, but also provide feedback to irrigation practitioners and analysts. This process is often limited by the database structure (not oriented to data analysis) and by the enormous amount of information often produced by these systems. These findings underline the fact that RSCS are rarely designed taking into consideration the long-term feedback value of the information they store. These problems require the application of data mining techniques in order to produce useful information for the analysis of farmers' irrigation scheduling. Data mining concerns the extraction of useful information from large amounts of data (Han and Kamber, 2006). In order to obtain knowledge from large databases the first step is data cleaning, followed by data integration if different sources of information are used. Once all information sources are located in the same platform, data selection and transformation will be required if only part of these data is useful or if data presentation is not adequate. Data mining will be followed by pattern evaluation and knowledge presentation.

3.3. Irrigation performance in urban environments

The city of Zaragoza is located in the central Ebro basin (northeast of Spain), and has a population of 682,000. The total population in the Ebro basin is 2.75 million. Urban water use in the Ebro basin has been estimated as 524 M m^3 yr^{-1}, representing 7 % of the total basin water use (Confederación Hidrográfica del Ebro, 2010). This figure is small in comparison with other developed urban areas. This is the case of many cities in the USA, where Kjelgren, Rupp and Kilgren (2000) reported that landscape irrigation accounted for 9 to 48 % of total municipal water use. The small percentage of urban to total water uses in the Ebro basin can be attributed to its low population density (35 inhabitants km^{-2}) and to the intensity of irrigated agriculture.

The relatively small contribution of urban water use to total Ebro basin water use should not lead to an underestimation of the importance of urban water use in the basin. In fact, urban uses require high water quality (due to the need for purification) and treatment as sewage water. As a consequence, urban water is far more expensive than agricultural water. The variable cost of agricultural water fluctuates from 0.03 to 0.10 € m^{-3}, while the variable cost of urban water in Zaragoza ranges from 0.16 to 0.76 € m^{-3} (Ayuntamiento de Zaragoza, 2004). Several studies have shown the effect of landscape irrigation water cost on the control of excessive irrigation. This is particularly true in areas characterized by low-middle income and high irrigation water cost (Domene and Saurí, 2003). Hurd et al. (2005) showed that water cost was closely related to the choice of landscape species in New Mexico (USA). In general, residential water use is characterized by inelastic demand (Renzetti, 2002): demand variation is a smaller ratio than the ratio of water cost variation. Additionally, Boland et al. (1984) concluded that the magnitude of this inelasticity depended on the specific location, probably depending on the average income.

In most private landscapes in Spain, water used for irrigation is potable water. As a consequence, poor landscape irrigation performance results in high economic and environmental costs. In addition, the Spanish water act gives the highest priority to urban uses in the case of drought. As a consequence the characterization of landscape water use is a valuable tool to rationalize water consumption in urban environments and in whole river basins. Landscape irrigation can become a key local water use in the presence of water shortages.

At the beginning of the 21st Century, high urban water cost and recurrent droughts motivated several water saving campaigns in Zaragoza and other cities in Spain (Parés-Franzi et al., 2006). These campaigns focused on a number of issues, including the reduction of irrigation water use in public landscapes. However, the irrigation of private landscapes did not receive much scientific or political attention. The main activity regarding private landscapes was the distribution of leaflets explaining xeriscaping practices at the nurseries supplying ornamental plants to local citizens.

In Zaragoza (as in the rest of Spain), the irrigation of private landscapes has increased in recent years due expanding suburbs as incomes have increased. In these suburbs, most housing developments include private landscapes. By the end of the 20th century, only 5 %

of the local homes had private landscapes (Ayuntamiento de Zaragoza, 1999). However, over the past decade a clear trend for the horizontal expansion of the city has been observed. Water used in landscape irrigation at the new urban development has been documented to reach 56 % of the total water use (Loh and Coghlan, 2003).

In Mediterranean countries turf is generally treated as a positional good (Hirsch, 1976), due to its shortage in natural landscapes. For this reason, it is common to find it as a predominant species in the landscapes of Zaragoza (whether private or public), accompanied by other species typical of temperate, humid climates. The main disadvantage of these species is their high water requirements, which can not be met by the typical precipitation of semiarid environments such as Zaragoza.

Water requirements for landscapes are calculated taking into account different factors, the two most important being the local climate and the type of species present in the landscape. Other factors include the coexistence of two or more species in the same area (i.e., turf, trees or shrubs) and factors modifying the climate, such wind exposure. Research work determining landscape water requirements (LWR) usually follows one of three methodological approaches: The first option is to put landscape water requirements at the level of ET_0 values (Haley et al., 2007). This comparison is logical if most of the landscape area is turf. The second option is based on direct estimation of landscape water requirements through the use of instruments such as volumetric soil water sensors (Morari and Giardini, 2001; White et al., 2004) or weighing lysimeters (Brown et al., 2001). The last group of authors (Domene and Saurí, 2003; Contreras et al., 2006) follows the methodology proposed by Costello et al. (2000), developers of the WUCOLS method for determining landscape water requirements. The WUCOLS method is based on ET_0, and uses an ad hoc procedure to estimate the coefficients that replace the crop coefficient by a landscape coefficient.

Overirrigation has been reported as common in private landscapes, particularly during the fall season (Hunt et al., 2001; White et al., 2004; Endter-Wada et al., 2008), and in small landscapes (Kjelgren et al., 2000). This is due to the delay in changing the irrigation schedule from summer to fall (a season in which landscape irrigation requirements sharply decrease). These results are in contrast with local agricultural irrigation. Overirrigation is not common in the agricultural irrigated areas of Spain, particularly if pressurized systems are used. Adjustments of irrigation depth to crop water requirements or even moderate underirrigation are common findings in specialized research works (Lorite et al., 2004).

Irrigation performance (based on the analysis of irrigation water use and on its comparison with irrigation requirements) has been assessed by a number of authors in private and public landscapes. These works reported differences resulting from differences in water price, income (either individual or average in the municipality), plant species, landscape size, irrigation systems, presence of irrigation controllers and feedback of information to the users (Hunt et al., 2001; Domene and Saurí, 2003; Syme et al., 2004; Domene and Saurí, 2006 and Parés-Franzi et al., 2006). Urban water use in private landscapes composed of turf, trees and shrubs has been reported in three cities in Spain: Barcelona (Domene and Saurí, 2003; Domene and Saurí, 2006; Parés-Franzi et al., 2006), Murcia (Contreras et al., 2006) and Madrid (Moreno et al., 2007). These references reported that in the local conditions of Spain landscape irrigation water use was related to the municipality income level and to the landscape ownership (private vs. public).

The presence of irrigation controllers is an important issue, since their low cost has resulted in widespread use. Standard (time-based) irrigation controllers (those in which the user has to enter the irrigation schedule) have been found to increase the irrigation water volume as compared with manual irrigation control (Loh and Coghlan, 2003; Syme et al., 2004 and Endter-Wada et al., 2008). This fact seems to be related to saving time, instead of saving irrigation water. Adjusting the irrigation controller to changes in water requirements is a time consuming task, and many users perceive it as too complicated.

On the other hand, advanced irrigation controllers resulted in significant reductions in water use. A number of research studies analysed the use of irrigation controllers equipped with rainfall sensors (St. Hilaire et al., 2008; McCready et al., 2009) or with the capacity of obtaining ET_0 estimates (Hunt et al., 2001; Quails et al., 2001; Aquacraft-Inc, 2003; Devitt et al., 2008; Davis et al., 2009). These studies demonstrated that advanced irrigation controllers permit to reduce water use by 11 to 75 % as compared with manual irrigation. In addition to conserving irrigation water, some of these studies (Hunt et al., 2001; Devitt et al., 2008) reported an increase in the visual quality of landscape.

Water price is one of the most important factors controlling water use (Baumann et al., 1998; Domene and Saurí, 2003). Consequently, an adequate water pricing policy seems to be one of the most important tools for decreasing private landscape irrigation water use. When landscape irrigation water is obtained from an agricultural irrigation water supply network, water price is generally too low to induce water conservation in landscape uses.

3.4. Irrigation performance in agricultural environments

All water users share responsibilities in water quantity and quality conservation. Among these users, farmers must obtain adequate irrigation performance standards, since water is a decisive input in their farming operations. Irrigation performance assessments are required for hydrological planning and as a first step to improve water management. The different levels of Public Administration are currently increasing control on water resources, and focusing on the river basin as the primary geographical unit of water policy (Jensen, 2007). At the European level, the implementation of the Water Framework Directive (European Parliament, 2000) requires water application data from all economic sectors. In water-short Mediterranean countries there is a need for structured analyses on irrigation water consumption and irrigation performance.

A number of procedures have been described to assess on-farm irrigation efficiency. The classical work by Merriam and Keller (1978) was one of the first compilations of irrigation performance indicators. Burt et al. (1997) produced an update of irrigation performance indexes, stressing the hydrological implications of irrigation performance. These authors proposed three irrigation performance indexes that could be applied to time intervals exceeding one irrigation event: irrigation efficiency, irrigation consumptive use coefficient, and irrigation sagacity.

In this work, the ARIS index (Annual Relative Irrigation Supply), proposed by Malano and Burton (2001), was used to estimate irrigation performance. This index represents the ratio of irrigation supply to crop irrigation demand as:

$$\mathrm{ARIS} = \frac{\mathrm{IWA}}{\mathrm{IR_n}} \qquad [1]$$

where IWA is the irrigation water applied ($m^3\ ha^{-1}$) and IR_n are the seasonal net irrigation requirements ($m^3\ ha^{-1}$).

An ARIS value of 1.00 implies that irrigation water application is equal to the net crop water requirements. This situation can not lead to a fulfilment of water requirements since 100 % irrigation efficiency can not be attained under commercial field conditions. Clemmens and Dedrick (1994) classified irrigation systems according to their potential application efficiency. In an optimistic scenario, the best systems attained 90 % efficiency. If water application is made equal to the net irrigation requirements with an efficiency of 90 %, the resulting ARIS value is 1.11. Under this efficiency hypothesis, any ARIS value below 1.11 implies seasonal underirrigation. Accordingly, ARIS values above 1.11 imply seasonal overirrigation. Since ARIS is a seasonal index, during short periods percolation may happen even with ARIS < 1.11, and deficit may happen even with ARIS ≥ 1.11. A detailed analysis of a particular irrigation system would be required to assess its efficiency, and therefore to establish the specific ARIS value separating seasonal deficit from seasonal excess irrigation.

The ARIS index can be used to estimate the degree of seasonal over- or underirrigation at a given field. If a field is overirrigated, ARIS will be related to irrigation efficiency. Improving irrigation efficiency constitutes a major goal for irrigation engineers and managers, since it means adjusting irrigation to crop water requirements (including salt leaching requirements). However, improving irrigation efficiency does not imply saving water. Lecina et al. (2010), analysing a large irrigation project in the Ebro Basin, concluded that irrigation modernisation (changing from surface to sprinkler irrigation) will result in improved irrigation efficiency, increased water consumption (the sum of estimated beneficial and non-beneficial consumption increased by 19-46 %, depending on the future scenario) and improved quality of the return flows. This reference illustrates with numbers the impact of improving irrigation efficiency in the area of study, and further supports previous analyses (Perry, 1999; Playán and Mateos, 2006; Perry, 2007, Ward and Pulido-Velázquez, 2008).

The Ebro basin, located in NE Spain, is one of the most intensively irrigated river basins in Europe (Wriedt et al., 2008), with about 0.8 million hectares of irrigated land. No work has reported the ARIS index in this area, but the low data requirements that characterize ARIS permit to estimate it from other performance indicators. Thus, Faci et al. (2000) analysed a surface irrigated district in the central Ebro basin grown with field crops, which yielded

ARIS values of 2.00 for grain corn and 0.86 for sunflower. Lecina et al. (2005) analysed a similar irrigation district in the Ebro basin, which resulted in average ARIS values of 2.05 for 2000 and 1.51 for 2001. This interseasonal difference was attributed to moderate water scarcity in 2001, which resulted in better irrigation management. Dechmi et al. (2003a) analysed a sprinkler irrigated district in the Ebro basin characterized by high energy costs for water pumping. The average crop ARIS were 0.78 for alfalfa and 0.90 for grain corn. In two sprinkler irrigated watersheds Cavero et al. (2003) found ARIS values ranging from 0.94 to 1.12 for corn, from 1.03 to 1.15 for alfalfa and from 0.57 to 1.09 for sunflower. In a wind exposed solid-set irrigation district, Zapata et al. (2009) reported data leading to average estimated ARIS values of 1.25 for grain corn and 1.59 for alfalfa. These authors concluded that the performance of this sprinkler irrigated area was strongly limited by meteorological conditions. The comparison of these works in the Ebro basin suggests that irrigation performance can be related to the irrigation system, to water scarcity and cost and to soil and climatic factors. These limited sources of information do not permit to develop average ARIS information at the basin scale, establishing differences between crops and irrigation systems.

Lorite et al. (2004) applied the ARIS index to the Genil-Cabra irrigation district (7,000 ha), located in the Guadalquivir basin, southern Spain. This area is characterized by annual ET_0 and precipitation of 1,300 and 600 mm, respectively, and a maximum seasonal water availability for irrigation of 5,000 $m^3\ ha^{-1}$ (García-Vila et al., 2008). The district was equipped with hand-move sprinkler and drip systems. The authors focused on seven crops and used data from four irrigation seasons. They found ARIS values ranging from 0.22 in sunflower to 1.19 in sugar beets, indicating severe underirrigation and slight overirrigation, respectively. Garcia-Vila et al. (2008) analysed the ARIS index in the same study area, but used 15 irrigation seasons. The average ARIS value for all crops was 0.60. Considering the different crops, these authors found ARIS values ranging from 0.23 (sunflower) and 0.28 (winter cereals) to 0.79 (cotton). Even though the Genil-Cabra area has some similarities with the Ebro basin, there are some relevant differences: 1) on-farm surface irrigation is common in the Ebro basin but this irrigation method is not used in the Genil-Cabra area; 2) water restrictions apply every year at the Genil-Cabra district; and 3) the Ebro basin is much larger in area than the Genil-Cabra district, and therefore more heterogeneous in climate and cropping patterns.

Research results from other parts of the World also permit to estimate ARIS. Thus, data from Molden et al. (1998) corresponding to surface irrigated areas located in different countries, led to regional ARIS values ranging from 0.50 to 4.16. Regarding crops, Molden (1997) collected data in India leading to ARIS values of 1.54 for wheat and 1.64 in cotton.

In the last years, irrigation performance indexes have been extended to include economic terms. Water productivity has gained importance due to the relevance currently given to economic efficiency in water allocation. Playán and Mateos (2006) presented an analysis on water productivity and discussed formulations based on yield (technical productivity, kg m^{-3}) or monetary units (economic productivity, € m^{-3}). When productivity is expressed in monetary units, the gross income or the net benefit can be used in the calculation. The type of crop and the production strategy have a relevant influence on monetary water productivity indexes.

The technical productivity of irrigation water (WP_T) can be defined as the yield (Y, kg ha^{-1}) obtained per volume of irrigation water application (IWA, m^3 ha^{-1}):

$$WP_T = \frac{Y}{IWA} \qquad [2]$$

WP_T has been reported in a number of research works (Igbadun et al, 2006; Fernández et al., 2007; Kahlown et al., 2007). WP_T has two relevant advantages: 1) it is a direct estimation of water productivity; and 2) it is not subjected to the time and space variability of economic data. Unfortunately, WP_T is not adequate to establish comparisons between crops, because yields, profits and costs can be very different. Alternative approaches to productivity are available to solve this problem. One of these approaches is the gross economic productivity of irrigation water (WP_{Eg}). It can be determined as the ratio between the gross income of a crop (I_g) and the seasonal volume of irrigation water (IWA):

$$WP_{Eg} = \frac{I_g}{IWA} \qquad [3]$$

Molden et al. (1998), Perry (2001), Ahmad et al. (2004) and Jalota et al. (2007) determined WP_{Eg} for rice in different areas of the world, ranging from 0.043 to 0.087 € m^{-3}. Perry

(2001) and Jalota et al. (2007) obtained values ranging from 0.106 to 0.053 € m^{-3} for grain corn and from 0.121 to 0.100 € m^{-3} for wheat. Buendía-Espinoza et al. (2004) in pressurized irrigation systems in Mexico found that WP_{Eg} ranged from 1.65 to 2.68 € m^{-3} in tomato and from 2.14 to 2.34 € m^{-3} in pumpkin. In Spain, Lorite et al. (2004) found average values of 0.28 € m^{-3} in winter cereals, 0.23 € m^{-3} in grain corn and 2.21 € m^{-3} in garlic.

An accurate economic assessment of water productivity requires using not only income, but also costs. This is the case of the Net Economic Productivity of irrigation water (WP_{En}, € m^{-3}), which permits to compare the water productivity of different areas or crops. WP_{En} is determined as the ratio of the net crop margin (M_n, € ha^{-1}) to IWA:

$$WP_{En} = \frac{M_n}{IWA} \quad [4]$$

Jalota et al. (2007) and Perry (2001) obtained WP_{En} values from 0.020 € m^{-3} for rice and 0.034 for grain corn to 0.081 € m^{-3} for wheat.

The abovementioned indexes are influenced by factors such as the irrigation system, irrigation scheduling, fertilization, irrigation water quality, crop variety, climate, and soil characteristics. Consequently, large spatial and temporal variability has been reported.

4. MATERIALS AND METHODS

4. MATERIALS AND METHODS

A wide range of methodologies were used in this research. For the characterization of drops, techniques based on photography and image treatment were used. For the study of irrigation scheduling and irrigation performance, statistical and data mining techniques were applied. In the following sections, these techniques are presented and their particular application to each of the main scientific objectives of this thesis is described.

4.1. Characterization of drops emmited by an agricultural sprinkler

The characterization of the drops emmited by an agricutural sprinkler was achieved by the obtention of drop photographs using a commercial camera and the analysis of these drop photographs using image treatment software. The proposed technique permits to directly measure drop diameter, velocity and angle.

4.1.1 Experimental set up

A VYR35 impact sprinkler (VYRSA, Burgos, Spain) was used in all experiments. This model is commonly used in solid-set systems in Spain. The sprinkler was equipped with a 4.8 mm nozzle (including a straightening vane). An isolated sprinkler was installed at an elevation of 2.15 m and operated at a nozzle pressure of 200 kPa. The sprinkler revolution time was 27.5 s. A volumetric water meter was used to estimate sprinkler discharge. The experimental runs were performed at the CITA farm located in Montañana, Zaragoza (Spain). A plot was chosen which was protected from the prevailing winds by a windbreak. Experiments were performed in periods of inappreciable wind.

4.1.2 Characterization of the sprinkler radial application pattern

In order to achieve this objective, 28 pluviometers were installed on the experimental plot along a sprinkler radius, covering distances from 1.5 m to 14.0 m, with 0.5 m interval. The pluviometer dimensions were in compliance with the ISO 15886-3 norm. The irrigation test lasted for two hours, during which 2.495 m^3 of irrigation water were applied (average discharge of 0.347 L s^{-1}).

4.1.3 Preliminary photographic experiments

Using a relatively low shutter speed, drops are represented in the photographs as cylinders, thus permitting the identification of drop diameter and length of run (by comparison with a photographed reference ruler), and vertical angle. Drop velocity can be derived from the length of run and the shutter speed.

Preliminary experiments were performed to identify optimum camera operation conditions for outdoor drop identification. The camera zoom was always set at 70 mm. After trying several background screen colours, black was chosen as the best option for drop characterization. In a second step, different shutter speeds (100, 125 and 160) and diaphragm openings (from F4.5 to F29) were tested. The chosen combination was a shutter speed of 100 (1/100 s) and F11. These camera adjustments resulted in sharp drop cylinder images.

In all subsequent experiments, the camera and the screen were installed as depicted in Fig. 1.1, to allow for drops to fall between them. The screen was built to suit the needs of the experiment. It consisted of a plastic rectangle of 0.30 x 0.40 m covered with a black cloth to prevent drops on the plastic material from shining and thus disturbing the characterization of falling drops. A reflecting metallic lateral was mounted on the side of the screen (opposite to the sun) to increase the drop brightness by duplicating the source of light (sun and reflector). The screen was installed at a distance of 1.00 m from the camera objective. The reference ruler was installed on the screen, at a distance of 0.25 m from it (0.75 m from the camera objective). The camera was manually focused on the reference ruler.

Subsequently, tests were performed to determine how many photographs could be taken when shooting in continuous mode and what the speed of picture taking was. These values depend of the selected photo quality. Quality “L” (3,872 by 2,592 pixels) was selected because this was the highest available image resolution in JPEG format, and the picture taking speed was adequate (2.9 photos per second). The combination of photo quality, zoom regulation and distance to the target resulted in a density of 14-15 pixels mm^{-1}. As a consequence, drops of 0.5 mm would have a diameter of about 7 pixels, while drops of 5 mm would have a diameter of 70-75 pixels. Regarding the length of the drop trace (cylinder height), it fluctuated between 130 and 1,050 pixels, depending on drop velocity.

4.1.4 Validation of the proposed photographic method

An experiment was performed to validate the main features of the method. Drops were modelled using metallic spheres of known diameter and physically determined velocity. A digital micrometer was used to determine an average diameter of 4.49 mm, and a coefficient of variation in diameter of 0.69 %. The experimental density of the lead-based spheres was 11.2 Mg m^{-3}. A set of spheres was released from an elevation of 0.55 m over the 0 mark on the reference ruler. Photographs were used to determine sphere diameter and velocity. Due to the short trajectory of the spheres and the high metal density, acceleration was relevant when spheres were photographed. Consequently, for each sphere, the elevation from the release point to the centre of the photographed trajectory was determined. In order to test the photographic depth-of field and to estimate the related errors, spheres were released from five different points, differing in distance to the camera objective. The first release point was just above the reference ruler. The remaining four points were closer to the camera objective by 0.02, 0.04, 0.06 and 0.08 m, respectively. In all five cases, the camera objective was focused to the reference ruler.

Diameter validation consisted on comparing micrometric measurements and photographic estimates of sphere diameter at different distances from the reference ruler. Regarding sphere velocity, the ballistic theory applied to drop movement was analysed (Fukui et al., 1980; Seginer et al., 1991). Under the experimental conditions the drag force was orders of magnitude smaller than the sphere weigh. As a consequence, sphere movement could be approximated by the free fall equation:

$$V = \sqrt{2\,g\,h} \qquad [5]$$

Where V is vertical velocity, g is the acceleration of gravity, and h is elevation from the release point.

4.1.5 Methodology for drop characterization: field procedures

Field experiments for drop characterization began at the experimental plot with the isolated sprinkler (Fig. 4.1), in sessions lasting between one and two hours. Nozzle pressure was controlled with a manometer and adjusted to 200 kPa. A radial line was marked on the soil extending from the sprinkler to the last observation point. The line was marked in every experimental period so that it formed a horizontal angle of about 5º with the sun. Observation points for drop photography were marked on the line at distances of 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5 and 12.5 m from the sprinkler. While the interval between observation points was usually 1.5 m, between the last two observation points the interval was 2.0 m. This interval was chosen so that photographs could be taken at 12.5 m, the last distance from the sprinkler at which drops could be appreciated at the camera elevation (0.80 m). It was judged interesting to photograph the drops reaching the largest distances from the sprinkler.

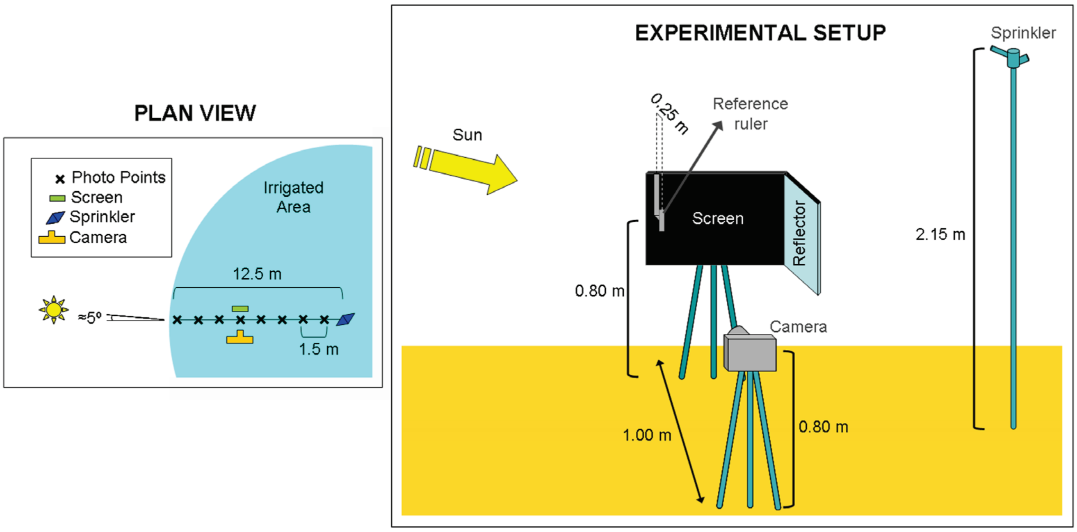


Figure 4.1. Experimental setup for drop characterization.

At each observation point, the camera and the screen were installed (Fig. 4.1). When the sprinkler jet approached the measurement line, the camera shooting was activated in continuous mode. Shooting stopped when drops could not be appreciated. Consequently, the number of photographs was different in each experimental run. In fact, this number depended on the time the jet stayed over the observation point (in turn dependent on distance to the sprinkler). This procedure was repeated between three and ten times at each observation point, depending on the local drop density (number of drops per unit photographed area). Drop density was very high near the sprinkler, while at the distal areas a large number of photographs were required to obtain a representative sample of the local drop population.

Although the sprinkler nozzle produces one compact jet of drops, the sprinkler impact arm takes some of its water to create a new, small jet at a certain horizontal angle. At distances of 6.0 and 7.5 m from the sprinkler, the time lag between the drops coming from the impact arm and those coming from the main jet was long enough to photograph both sources of drops separately. At smaller distances no distinction could be made, while impact arm drops were not observed at distances exceeding 7.5 m.

4.1.6 Methodology for drop characterization: office procedures

At every observation point a large number of photographs were taken. Some of them showed drops of adequate quality. These photographs were selected for further analysis using Microsoft Picture Manager®. The values of brightness, contrast and semitone were fixed at 60, 85 and 100 %, respectively, for all images.

The GIMP2© software (University of California, Berkeley, USA) was used for drop analysis. Drops adequately focused (located near the vertical plane containing the reference ruler) were numbered for future reference. Due to the available image resolution, drops not reaching 0.3 mm in diameter were discarded since it was impossible to assess if they were focused. The following step was to measure drop length, angle respect to the horizontal (setting the 0º at the line starting at the camera objective and perpendicularly intersecting the sprinkler riser), and drop diameter (correcting the number of horizontal pixels with the drop angle). If for a given drop the complete cylinder was not represented in the photograph, drop velocity was not measured. However, the drop diameter and angle were added to the drop database. All values were initially registered in pixels and transformed to mm using the pixel mm^{-1} ratio obtained from the analysis of the image of the reference ruler. Histograms of the three analyzed variables were produced at each observation distance.

Drop diameter was combined with the sprinkler application pattern to estimate cumulative applied volume at a certain distance from the sprinkler.

4.2. Irrigation scheduling in pressurized networks: the human factor

The analysis of irrigation patterns in the irrigated area of Candasnos permitted assessing the importance of different factors in irrigation decsion making in pressurized irrigation. Particular attention was paid to the human factor.

4.2.1 Area description

Data presented in this study were obtained at the Candasnos irrigation district. The district makes part of the *Riegos del Alto Aragón* Project (Lecina et al., 2010). This irrigated area is located in North-eastern Spain, and covers 6,937 ha. Irrigation systems have been installed in an area of 4,916 ha. The area presents a semi-arid climate, with very hot summers and long, cold winters. The local meteorological characterization in the years of study (2004-2008) was based on the data obtained at the agrometeorological station of Candasnos, belonging to the SIAR network (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011). A summary of the agrometeorological characterization is presented in Table 4.1. Annual daily temperature (T) fluctuated between -3.9 and 27.7 ºC, with an average of 13.8 ºC. Annual average reference evapotranspiration (ET_0) and precipitation (P) in this period were 1,232 mm and 324 mm, respectively. The average wind speed (WS) was 2.3 m s^{-1}, a value that often separates adequate and low solid-set sprinkler irrigation performance (Playán and Mateos, 2006). Among the study years, 2005 was characterized by severe drought induced by low storage at the main *Riegos del Alto Aragón* reservoirs. As a consequence, farmers' irrigation water use was limited to 4,500 m^3 ha^{-1}.

Irrigation water is locally stored at a reservoir located at the head of the pressurized collective network. The difference in elevation between the reservoir and the irrigation district hydrants provides the network with natural pressure. Furthermore, the reservoir is directly filled from the Monegros supply channel (no need for pumping). As a consequence, the irrigation district faces irrelevant energy costs. Irrigation district hydrants have discharge limiting valves. The hydrant discharge ranges from 8 L s^{-1} to 80 L s^{-1}. The most common maximum hydrant discharges are 8, 10 and 12 L s^{-1}. These discharges derive from a hydrant design criterion of 1.2 - 1.3 L s^{-1} ha^{-1}. There are exceptions to this rule, represented by maximum values of 4.1 L s^{-1} ha^{-1} (additional discharge for small plots) and minimum values of 0.5 L s^{-1} ha^{-1}.

Table 4.1. Agrometeorological characterization of the Candasnos Irrigation Disctrict in the years of study (2004-2008). Values of Temperature (T), Wind Speed (WS), Precipitation (P) and Reference Evapotranspiration (ET_0) are presented, along with the month of maximum and minimum values.

YEAR	2004		2005		2006		2007		2008		Average
	Value	Month	Value	Month	Value	Month	Value	Month	Value	Month	Value
Average Daily T (ºC)	13.6	-	13.5	-	14.6	-	13.7	-	13.5	-	13.8
Maximum Daily T (ºC)	27.8	JUL	27.9	JUL	28.1	JUL	27.5	AUG	27.1	AUG	27.7
Minimum Daily T (ºC)	-0.6	JAN	-4.3	DEC	-2.9	DEC	-2.1	JAN	-9.6	DEC	-3.9
Average Daily WS (m s^{-1})	2.17	-	2.53	-	2.18	-	2.43	-	2.11	-	2.3
Maximum Daily WS (m s^{-1})	9.37	JAN	10.68	FEB	8.97	MAR	9.26	JAN	9.60	MAR	9.6
Maximum Daily P (mm)	29.6	APR	49.2	JUN	27	SEP	14.2	APR	41.8	MAY	32.4
Total P (mm)	359.4	-	335.6	-	262.2	-	194.4	-	470.6	-	324.4
Total ET_0 (mm)	1141	-	1319	-	1292	-	1261	-	1147	-	1232

A cable-based remote surveillance and control system (RSCS) was installed at the Candasnos Irrigation District in 1998. The system was set to record hydrant discharge every ten minutes (approximately). The RSCS software and computers were upgraded just before this research was performed. This fact made the exploration of the four old hard drives easy: they could be taken to the laboratory for complete analysis. This RSCS contains the oldest data of this nature in the Ebro basin, and therefore represents a very interesting opportunity for the analysis of irrigation patterns. Unfortunately, the RSCS system does not record irrigation management variables. This problem was solved in 2004, when the district started making full use of the Ador software for the management of irrigation districts (Playán et al., 2007). As a consequence, the data series concerning plots, hydrants, irrigation systems, water users, water uses (crops) and time evolution of hydrant discharge is available from 2004 to 2008. This period corresponds to the time frame of this study.

The irrigation district showed an average of 276 landowners and 131 irrigators in the years of study. The difference in number between landowners and irrigators derives from the need of cultivate large extensions of irrigated area in order to obtain an adequate economic return. The average area was 17.43 ha for landowners and 36.85 ha for irrigators. Some of the irrigators do part-time farming in the area.

The irrigation system information was individually collated by observing aerial photographs of irrigated area (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011). The most common irrigation system in Candasnos is solid-set, present in 53 % of the irrigation district area, followed by pivot (40 %) and drip irrigation (7 %). In some plots, pivot(s) and solid-sets are found in combination. In these cases the central part of the plot is pivot irrigated, while the corners are irrigated by a solid-set. The spatial distribution of Irrigation systems was also available from the Ador database.

Crop distribution in the irrigation district changed each year of study (from 2004 to 2008). Summer field crops prevail in the study area: alfalfa and corn occupy on the average 20 % and 40 % of the district area, respectively. Other relevant crops in the area are the sequence barley/corn and drip irrigated peach, with respective percentage areas of 15 and 7 %.

Water management in the study area is based on previous water orders. The system is located at the downstream end of a 223 km canal system (Lecina et al., 2010). As a consequence, water used in Candasnos needs to be ordered to the Project office two days in advance. This time is an approximation of the travel time from the project reservoirs to the district reservoir. Farmers file individual water orders at the district office. Orders are stored in the Ador database. Every day, the water orders filed for the day after tomorrow are summarized and sent to the project office via Internet. Water orders permit to document water use in parallel or the RSCS system, providing a means for the validation of water use information. However, the need for previous water orders reduces farmers' freedom to use irrigation water: once water is ordered the farmer must use it, since the capacity of the district reservoir (218,000 m^3) only represents 4.4 mm when distributed to the whole irrigated area.

4.2.2 Extraction of knowledge: data mining

An exploratory data analysis was performed on the contents of the RSCS hard drives. The tabular information contained in the system only detailed daily water deliveries per hydrant. However, a graphic utility presented daily evolution of discharge per hydrant. As a consequence, a binary search was started in the RSCS system files in order to locate time-discharge records per hydrant. The original records were found in binary Flow Files (FF) and decrypted. Discharge registers were recorded with time intervals ranging between 11 and 18 min. Decryption did not permit to assess the hydrant code in the system used for tabular reports (corresponding to the project hydrant code).

The association between decrypted information and hydrant codes was obtained by comparison of the tabulated and computed daily water delivery per hydrant. The first step was to integrate the FF discharge values into daily delivery volume and standardized semi hourly values (FFst). A specific software application compared the water application patterns and performed the association. Manual supervision was used to provide additional certainty. A total of 256 hydrants were associated to FFst discharge files, creating HFFst files. Additionally, the annual water delivery derived from HFFst files was compared to annual water billed to the irrigators through the Ador software. In cases where differences between the two data sources exceeded 8 %, a case by case analysis was performed to detect anomalies, which were often located at the HFFst files (periods without RSCS data).

In a further step, a file was produced for each hydrant summarizing the yearly irrigation events. For each identified event, the date and time of irrigation start and end were recorded, as well as the percent daytime and nighttime irrigation, the average discharge and the irrigation volume. Daytime irrigation was assigned between 8.00 and 20:00 (local civil time). This file contained information about 75,546 irrigation events corresponding to 1,216 hydrant-year combinations.

4.2.3 Selection of valid information

A relational database was created containing all data sources used for this research: HFFst, irrigation events, daily delivery volume per hydrant, agrometeorological data and a number of tables copied from the Ador database: crops, irrigation network, hydrants, irrigation system, landowners, irrigators and plot areas.

A series of queries to the relational database were used to obtain specialized information. In a first step, graphics of daily delivery volume were produced for the available combinations of crop, hydrant and year. Individual visual inspection of these graphs was used to discard cases of hydrant-year combinations revealing failed crops or clear errors in crop declaration by farmers. In a second step, a table was created containing hydrant name, cadastral identification, plot area and irrigation system. Since two sources of information were available for plot irrigation systems, plots showing discrepancies were discarded from the database. Finally, hydrants shared among various plots were eliminated because it was not possible to distinguish from the RSCS the plot receiving a given irrigation event. As a consequence of this process, a final database was established containing 39,909 irrigation events resulting from 585 hydrant-year combinations.

4.2.4 Statistical analyses

The file containing irrigation events was used to elaborate basic statistics about frequencies and general trends of the irrigators' behaviour. The number of hydrants simultaneously irrigating in each semi-hourly period was used for comparison with agrometeorological data. This permitted to analyse the influence of meteorology on sprinkler irrigation decision making. The meteorological factors used in this study included wind velocity, daily precipitation, temperature and relative humidity.

The irrigation events file was used for more involved analyses. In a first step, a hierarchical cluster analysis was used on the following analysis: weekly number of irrigation events, standard deviation of weekly irrigation events and mode of the starting hour of the irrigation events. This classification was performed to identify homogeneous groups of irrigation decision making in the irrigation district. Five variables were used as candidates for the classification: the weekly average irrigation duration, the standard deviation of weekly average irrigation duration, the average number of weekly irrigations, the standard deviation of the average number of weekly irrigations, the modal range of the starting irrigation time and the percentage of irrigations in which irrigation started during the modal range. The variables resulting in the most homogeneous groups were the average number of weekly irrigations, the standard deviation of the average number of weekly irrigations and the modal of range of the starting irrigation time.

Differences among these groups were analysed using ANOVA and Duncan tests. In a second step, the influence on irrigation decision making of the year, crop, irrigator, plot area, hydrant characteristics and irrigation system was assessed analysing frequencies and using categorical regression. These analyses were performed using the SPSS v.19 statistical software (Statistical Package for the Social Sciences, 2010). Finally, semi hourly hydrant discharge data were transformed into binary semi hourly files with the objective of plotting the identified irrigation patterns.

4.3. Irrigation performance in urban environments

The correspondence between irrigation application and irrigation requirements was analised in a urban environment. The study area was formed by a group of private household landscapes located in Zaragoza (Spain). The main characteristics of these landscapes were documented using aerial photographs.

4.3.1 Area description

The Montecanal neighborhood was chosen to analyze landscape irrigation performance in selected households. A household consists of all private residential property (building + lanscape + paved areas). Montecanal is a suburb of Zaragoza (Northeast Spain; UTM coordinates 41.6 and -0.9), whose residents are characterized by relative medium-high income. The climate in the zone is semiarid, with very hot summers and long, cold winters. The annual average of ET_0 and precipitation are 1,198 mm and 337 mm, respectively.

Montecanal makes an interesting case study since potable water and irrigation water are supplied by two different networks. This is not a common feature in the world, and is certainly infrequent in Spain. While potable water follows a standard treatment, irrigation water is directly supplied from the “Canal Imperial”, a canal constituting one of the main sources of urban water for Zaragoza, as well as supplying a large agricultural irrigated area. Each household in Montecanal is equipped with two water meters: One for indoor potable water and one for outdoor water, largely used for landscape irrigation. The maximum water meter error is ±5 % for minimum discharge and ±2 % for maximum discharge. The water price is different for each network. In the period 2005-2007, the cost of potable water was of 0.76 € m^{-3}, while the cost of irrigation water was of 0.17 € m^{-3} (a cost ratio of 4.5).

The study area comprised 134 households occupying cadastral plots with areas ranging between 248 and 532 m2. The most common household area is 266 m2, corresponding to 89 % of the analyzed cadastral plots. The total study area is therefore about 5 ha. Most Montecanal households have their own landscape area, surrounded by a tall fence. Landscapes vary in size and species (the most common are turf, ornamental trees and shrubs). Only part of the outdoor area of each household is covered with vegetation. In some households, areas initially designed for landscape have been paved. Pressurized irrigation systems have been installed in the landscape areas. Sprinkler irrigation systems are common in areas where turf prevails. Drip irrigation systems prevail in landscapes planted with trees or shrubs. It is very common that a single household uses both irrigation systems, installed in different landscape areas. The use of time-based irrigation controllers is widespread in the area.

4.3.2 Household area determination

The characterization of household landscapes was performed using color aerial photographs of the city of Zaragoza obtained from the SITAR (Territorial Information Service) of the Government of Aragón (Government of Aragón, 2008). These images, characterized by a pixel size of 0.1 x 0.1 m, have undergone radiometric and geographic corrections.

The first step in this analysis was to locate each household in the cadastral database. A Geographic Information System (Arcview© GIS 3.3) was used to measure the area of outdoor water uses: landscape (vegetated area) and swimming pools. Three polygon layers were created in the GIS: landscape, trees and shrubs, and swimming pools. The household architectural design often implied the existence of more than one vegetated area. The area occupied only by turf was obtained as the difference between the landscape area and the area devoted to trees and shrubs. An algorithm was applied to determine the area under each category in each household. At the end of this process, the landscape area (divided into turf on one hand, and trees and shrubs on the other) and swimming pool (if there was one) was obtained for each household. The rest of the household area was occupied by the building and the surrounding paved areas.

4.3.3 Water records

Bi-monthly records were obtained for the two water meters installed at each household. The study period covered from March 2005 to October 2007. These data permitted us to determine bi-monthly water use for each type of water. The following codes were assigned to the recording periods: Jan-Feb, Mar-Apr, May-Jun, Jul-Aug, Sep-Oct and Nov-Dec. Since irrigation water delivery is interrupted from November to February, periods Jan-Feb and Nov-Dec only contain potable water records.

4.3.4 Agrometeorological data

Agrometeorological data were obtained from the closest automatic meteorological station belonging to the SIAR network (Sistema de Información Agroclimática para el Regadío, Agro-climatic Irrigation Information System). This network publishes daily FAO Penman-Monteith reference evapotranspiration (Allen et al., 1998) (ET_0, mm day^{-1}), precipitation (P, mm day^{-1}) and average temperature (T_m, ºC), among other variables. The SIAR network was installed by the Ministerio de Medio Ambiente, Medio Rural y Marino of the government of Spain (Ministerio de Medio Ambiente, Medio Rural y Marino, 2011), and is operated in partnership with regional Governments. In this work, ET_0, P and T_m records were obtained for the temporal frame of the study (Table 4.2). The highest values of ET_0 and T_m always corresponded to the Jul-Aug period (2005-2007), with average values of ET_0 of 387 mm and T_m of 23.5 ºC. ET_0 and T_m were slightly lower in May-Jun, with 326 mm and 19.8 ºC, respectively. In Mar-Apr and Sep Oct, ET_0 values were similar (with averages of 186 and 188 mm, respectively), but the differences in T_m were substantial: T_m was higher in Sep-Oct (average of 17.7 ºC) than in Mar Apr (average of 11.8 ºC). The lowest ET_0 and T_m corresponded to the winter periods. Precipitation was irregular (Table 4.2), with peaks in Mar-Apr of 2007 (158 mm), Sep-Oct of 2006 (132 mm) and May-Jun of 2005 (102 mm).

4.3.5 Irrigation requirements

The WUCOLS (Water Use Classifications of Landscape Series) method, proposed by Costello et al. (2000) was used to estimate landscape irrigation requirements. WUCOLS is based on the application of a landscape coefficient (K_L), which is multiplied by ET_0 to obtain the LWR. K_L is determined as the product of the species factor (k_s), the density factor (k_d) and the microclimate factor (k_{mc}):

$$K_L = k_s\, k_d\, k_{mc} \qquad [6]$$

Table 4.2. Agrometeorological data for 2005-2007 in the study area of Zaragoza.

Year	Period	Total ET_0 (mm)	Total P (mm)	Average T_m (ºC)
2005	Mar-Apr	195	25	11.3
	May-Jun	343	102	20.8
	Jul-Aug	388	5	23.6
	Sep-Oct	181	66	17.5
	Nov-Dec	66	35	6.5
2006	Jan-Feb	71	42	5.1
	Mar-Apr	191	53	12.5
	May-Jun	330	47	20.0
	Jul-Aug	395	25	24.1
	Sep-Oct	180	132	18.9
	Nov-Dec	55	29	8.1
2007	Jan-Feb	73	28	6.3
	Mar-Apr	172	158	11.6
	May-Jun	304	86	18.7
	Jul-Aug	377	28	22.9
	Sep-Oct	204	49	16.8

The species factor depends of the type of plant and the related water requirements of the species planted in the landscape. These values were tabulated by Costello and Jones (1994) for more than 2,000 species in six areas of California. Species were classified as presenting very low requirements (k_s < 0.10), low requirements (0.10 < k_s < 0.30), moderate requirements (0.40 < k_s < 0.60), and high requirements (0.70 < k_s < 0.90). In this work, a k_s value of 0.82 was assigned to turf. This value is consistent with the high requirements of these species and was obtained as a weighted average of the values reported by Brown et al. (2001). The k_s value assigned to trees and shrubs was 0.55, corresponding to species presenting moderate water requirements. This estimation took into account the most common species in private landscapes containing trees and shrubs.

These species fell within the category of moderate water requirements, although some of them showed high water requirements. For each household, only one value of ks was proposed. This value was a linear combination of the fractional area occupied by turf and trees and shrubs.

The density factor modifies the species factor, adapting to the collective leaf area of all species in the landscape. If trees or shrubs only partially cover the soil surface, k_d presents values ranging from 0.50 to 0.90. If the soil surface is completely covered by plants, k_d presents a value of 1.00. Finally, if two or more species coexist in the same piece of land (in different layers), k_d values ranging from 1.10 to 1.30 are assigned. In this work, a value of k_d of 1.20 was used in landscapes with turf and trees or shrubs. If the landscape only presented turf or trees and shrubs, a value of k_d =1.00 was used.

The microclimate factor depends on certain landscape characteristics which result in an increase or decrease of water requirements. In this work, a value of k_{mc} = 0.70 was applied in all cases, since all households were surrounded by tall fences. This value corresponds to landscapes located in protected areas (Costello et al., 2000).

Net irrigation requirements (IR_n) were determined from Eq. [7], in which Effective Precipitation (EP) was calculated using the method proposed by Brouwer and Heibloem (1986) for areas with slopes lower than 4-5 %:

$$IR_n = K_L\, ET_0 - EP \qquad [7]$$

4.3.6 Irrigation performance

Irrigation performance was evaluated comparing irrigation water applied (IWA) with IR_n. IWA values were transformed from volume (m^3) to depth (mm), considering the landscape area of each household. The ARIS index (Annual Relative Irrigation Supply), proposed by Malano and Burton (2001) was used as an indicator of irrigation performance (Eq. [1]).

The reported methodology is common to agricultural irrigation hydrology studies (Burt et al., 1997; Malano and Burton, 2001; Lorite et al., 2004). As a consequence, parallels between local agricultural and landscape irrigation can be established and discussed.

Time correlation in household IWA and ARIS was analysed taking the three study years in pairs. The goal was to establish if the water use patterns (resulting in under- or overirrigation) were stable in time for the analysed households, or if new patterns appeared every year.

The SPSS software (Statistical Package for the Social Sciences, version 19 for Windows, SPSS Inc, Chicago, USA) was used for statistical analysis. Dendrograms of hierarchical conglomerates were used to classify households according to water use indexes. The goal of cluster analysis is to uncover groups of observations from initially unclassified data. Agglomerative hierarchical techniques are a class of clustering techniques in which, in each iteration, the number of clusters decrease and the number of individuals in each cluster increase. The task of the researcher is to decide which step in the analysis (or which number of clusters) will be used for research (Landau and Everitt, 2004).

4.4. Irrigation performance in agricultural environments

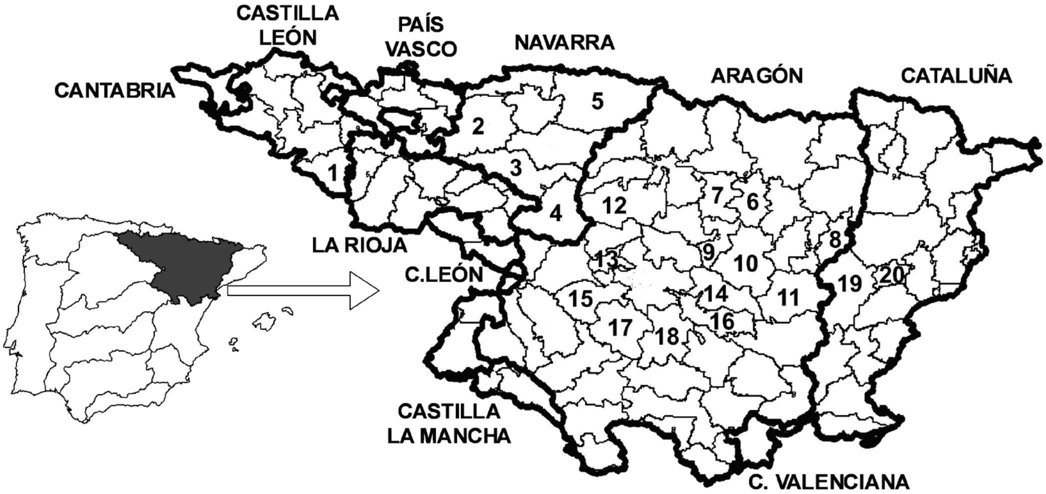
The correspondence between the annual irrigation volume and the irrigation requirements of agricultural crops was studied using standard performance indicators in this study comprising the main irrigated areas of the Ebro basin.

4.4.1 Area description

The Ebro basin extends over an area of 85,362 km^2, located mostly in Spain (84,415 Km^2), but also including parts of France and Andorra. In Spain, the Ebro basin partially covers nine autonomous regions, and is divided into 110 districts (Fig. 4.2) defined by the Water Basin Authority (*Confederación Hidrográfica del Ebro*, CHE). The shape of the Basin is triangular, with mountain ranges running along the three sides, and a depression in the central part where most of the irrigated areas are located. Soil characteristics are related to altitude and to the proximity to the Ebro river or its tributaries. Soils near the rivers can be classified as Fluvisol Eutric (FAO, 1974), while in the rest of the irrigated areas the most common soil types are Xerosol Gypsic and Xerosol Calcic. These soils are often salt-affected (*Confederación Hidrográfica del Ebro*, 2008).

A Mediterranean Continental climate is characteristic of most of the irrigated areas in the Ebro basin. Precipitation concentrates in autumn and spring. The average precipitation in the basin is 622 mm yr^{-1}. Its spatial distribution presents maximum values in the mountain zones and minimum values in the central depression (Martínez-Cob and García-Vera., 2004). At the irrigated areas, the average precipitation is usually in the range of 300-500 mm yr^{-1}.

According to the Moisture Index of the Thornthwaite Classification (Thornthwaite, 1931; Thornthwaite, 1948), the climatic type is humid or subhumid in the North and West of the Ebro basin. In the central part of the basin, the climate is semiarid or arid. According to the Thermal Efficiency index, the climatic type is Megathermal (A' with ET_0 > 1,140 mm) or Mesothermal (B'_4 with 1,140 mm ≥ ET_0 > 997 mm) at the central depression and the East of the basin, respectively. Towards the North or the West, the Thermal Efficiency index decreases to other Mesothermal climatic types such as B'_3 (997 mm ≥ ET_0 > 855 mm) or B'_2 (855 mm ≥ET_0 > 712 mm).



#	CHE District	Records	#	CHE District	Records	#	CHE District	Records
1	BELORADO	6	8	TAMARITE DE LITERA	29	15	ÉPILA-LA ALMUNIA	5
2	TIERRA ESTELLA	96	9	GRAÑÉN	107	16	QUINTO DE EBRO	18
3	RIBERA ALTA-ARAGÓN	288	10	SARIÑENA	220	17	CARIÑENA	8
4	RIBERA BAJA NAVARRA	420	11	FRAGA	91	18	BELCHITE	43
5	NAVARRA PIRINEOS	37	12	EJEA DE LOS CABALLEROS	85	19	SEGRIÀ	7
6	ANGÜÉS	4	13	ALAGÓN	4	20	PLÀ D'URGELL	2
7	HUESCA	14	14	PINA DE EBRO	133			

Figure 4.2. Location of the Ebro basin within the Iberian Peninsula. Division of the basin into Autonomous Regions and Confederación Hidrográfica del Ebro (CHE) districts. The number of records in each CHE district is indicated in the Table.

Within the Ebro basin there are approximately 784,000 ha of irrigated land (*Confederación Hidrográfica del Ebro*, 2008), representing one fifth of the irrigated area in Spain (Pinilla, 2002). Four regions located at the centre and East of the basin accumulate about 85 % (670,000 ha) of the irrigated area (Table 4.3). Surface irrigation is the most common on-farm system in the basin, occupying 69 % of the irrigated area. Sprinkler and drip irrigation follow, with 19 % and 12 % of the irrigated area, respectively (*Confederación Hidrográfica del Ebro*, 2008). Regarding the nature of the water source, virtually all irrigation developments in the Ebro Basin use surface water resources from the Pyrenees or Iberian mountains. These water sources largely depend on snowmelt and winter precipitation. As a consequence, the choice of herbaceous crops (more or less water demanding or drought tolerant) is determined by early indicators of seasonal drought, such as surface water storage at reservoirs and winter precipitation.

Table 4.3. Summary of the area occupied by selected crops in the Ebro basin and the Autonomous Regions for which data are available. The year of the data source is indicated for each region.

	Aragón 2003 (thousand ha)	**Cataluña 1999 (thousand ha)**	**Navarra 2003 (thousand ha)**	**La Rioja 2003 (thousand ha)**	**Total - (thousand ha)**
Winter field crops	100	28	16	9	153
Summer field crops	207	81	32	5	325
Fruit trees	42	50	4	5	101
Vegetable crops	11	4	17	9	41
Olive trees	11	8	2	1	22
Vineyards	9	3	11	5	28
Total	**380**	**174**	**82**	**34**	**670**

The long-term meteorological records from the Zaragoza area, located at the centre of the Ebro basin, can be used to illustrate the local irrigation water requirements (Martínez-Cob and García-Vera, 2004). Average seasonal precipitation amounts to 479 mm, while seasonal reference evapotranspiration amounts to 1,149 mm. For the summer period (May-September), the average values of precipitation and evapotranspiration are 237 and 874 mm, respectively. The dominance of summer evapotranspiration over precipitation is accentuated by the strong interannual variability of precipitation in Mediterranean climates. Rainfall is not relevant for summer crops, but can be very important for winter cereals, thus affecting spring water management.

Table 4.1 lists the irrigated land occupied by each of the six crop categories established in this work for the four abovementioned regions. Field crops are divided into two categories: winter and summer field crops. Additionally, two typical Mediterranean fruit crops are presented in separate categories: olive trees and vineyards. Field crops are mainly grown in Aragón (81 % of the irrigated area). Summer field crops are predominant in Cataluña and Navarra (47 and 29 % of the irrigated land, respectively), but fruit trees (29 % of the irrigated land in Cataluña) and vegetable crops (21 % of the irrigated land in Navarra) are also relevant. In La Rioja, vegetable and winter field crops are the most relevant categories, each one representing 29 % of the irrigated area. Two summer field crops characterized by high crop water requirements, alfalfa and grain corn, occupy 37 % of the irrigated area (Table 4.3).

CHE divides the basin irrigated area into large and small irrigation projects (*Confederación Hidrográfica del Ebro*, 2008). Large irrigation projects account for 58 % of the irrigated area. Most of them were developed by the Government, and are characterized by strong users' organizations enforcing water conservation through binomial water billing based on water records. Small irrigation projects (42 % of the irrigated area) correspond to ancient riparian canals where farmers pay water services by the hectare, and water applied is not recorded. Small irrigation projects typically use surface irrigation, and are located on the alluvial terraces of the Ebro river and its tributaries. Given the basin morphology, irrigation return flows resulting from low irrigation efficiency are often reused in downstream irrigation projects. This is particularly important in the case of small irrigation projects, where efficiency is presumed to be low. In large irrigation projects, a public-private modernization effort is currently replacing surface irrigation systems by pressurized systems.

4.4.2 Selecting irrigated plots

Martínez-Cob et al. (2005) set up the database which was used in this study. Cooperation with a number of irrigation districts, farmers' organizations, public water management companies and governmental offices permitted to assemble the data set, which contained information from 1,550 plots (11,528 ha). The largest data source was located in the Aragón region, where irrigation districts often use the Ador software for collective land and water management (Playán et al., 2007). This software records irrigation water application data at the plot level. The requisite for a plot to be included in the database is that the crop and IWA are known for a given irrigation season. This requisite excluded plots located in small irrigation projects.

4.4.3 Irrigation water application data

The original data set contained 2,754 records of seasonal irrigation water application on the abovementioned 1,550 plots. The irrigation seasons ranged from 1982 to 2005. A subset of 1,617 records of seasonal irrigation water application were analysed in this work. These are the records for which meteorological data was available to estimate crop water requirements using the FAO Penmann-Monteith method (Allen et al., 1998). The selected records correspond to 1,077 plots (10,475 ha), and to the irrigation seasons 1990-2005. Each record consisted of a combination of the plot characteristics (location, CHE district and area), the seasonal application of irrigation water, the crop, the year, and the irrigation system. These plots were located in 20 different CHE districts (Fig. 4.2). The average number of records per district was 81. The largest number of records was obtained at the *Ribera Baja de Navarra* CHE district, with 420. The CHE districts with the lowest number of records were *Plà d'Urgell* (2), *Angüés* (4) and *Alagón* (4). The irrigation season with the largest number of records was 2004 (665 records). Regarding the crops, the largest number of records corresponded to grain corn (944), alfalfa (236) and vineyards (99), while the lowest number of records corresponded to wheat (5), cherry (8) and potato (10).

4.4.4 Net irrigation requirements and irrigation performance

Most of the meteorological data used to estimate crop water requirements were obtained from the SIAR network of agrometeorological stations installed by the *Ministerio de Medio Ambiente, Medio Rural y Marino*, Government of Spain (2011). Additional data were obtained from the regional agrometeorological networks of Navarra (Government of Navarra, 2003) and Cataluña (Generalitat de Catalunya, 2002). These networks publish daily FAO Penman-Monteith reference evapotranspiration (ET_0, mm day^{-1}) and precipitation (P, mm day^{-1}), among other variables. Only in the case of Navarra it was necessary to determine FAO Penman-Monteith ET_0 (Allen et al., 1998) from the supplied meteorological variables. Effective precipitation was determined following Cuenca (1989).

Crop ET (ET_c) was determined as the product of ET_0 and the corresponding crop coefficient K_c (Allen et al., 1998). K_c values were obtained from local phenology (Martínez-Cob and García-Vera, 2004) and tabulated values (Allen et al., 1998). For olive trees the monthly K_c values proposed by Pastor and Orgaz (1994) for the conditions of Andalucía (southern Spain) were used. For alfalfa, K_c curves were determined for each period between hay harvests. For fruit trees, the four phenological stages defined by Allen et al. (1998) were slightly modified to adapt them to the phenological stages defined by agronomists and physiologists, following Girona (1996). The criteria adopted by this author were also followed to estimate ET_c under Regulated Deficit Irrigation (RDI) orchard management conditions for cherry, peach and vineyards. Finally, net irrigation requirements (IR_n) were determined for each crop as the difference between ET_c and effective precipitation.

The ARIS index was selected as an indicator of irrigation performance because: 1) It was proposed in the frame of a standardization effort led by IPTRID (Malano and Burton, 2001); 2) the variables required to estimate ARIS can be easily obtained in a large number of plots within a large area of study; and 3) ARIS has been successfully used to characterize irrigation performance in Mediterranean environments (Lorite et al., 2004; García-Vila et al., 2008). In this work ARIS was determined following Eq. [1].

The three abovementioned water productivity indexes (WP_T, WP_{Eg} and WP_{En}) were used in this work (Eqs. [2], [3] and [4]). For field crops, different yields were used for surface and solid-set irrigation (Cavero et al., 2003; Sisquella et al., 2004 and Lecina et al., 2010). The average farm economic data required to determine the WP_{En} index could only be obtained for Aragón and Navarre. Economic data for Aragón in seasons 2001 to 2005 was used (Ministerio de Agricultura, Pesca y Alimentación, 2002; 2003; 2004; 2005 and 2006). In the determination of WP_{En}, European Union subsidies (only affecting field crops) were considered in all cases. Irrigation water costs are typically charged by the cubic meter and by the hectare. These costs were available in Aragón due to the common use of the Ador software for irrigation district management (Playán et al., 2007). Average irrigation water costs resulted different in Aragon in pressurized irrigation districts (0.03 € m^{-3} and 40 € ha^{-1}) and in surface irrigation districts (0.01 € m^{-3} and 50 € ha^{-1}). In the case of pressurized irrigation the high cost per cubic meter is associated to the energy used at the pumping stations. Economic water productivity could only be determined for the database plots located in Aragón.

4.4.5 Statistical analysis

The statistical analysis of the dataset was performed using the SPSS software (Statistical Package for the Social Sciences, version 19 for Windows, SPSS Inc, Chicago, USA). The analytical procedures involved ANOVA and cluster analyses.

5. RESULTS AND DISCUSSION

5. RESULTS AND DISCUSSION

5.1. Characterization of drops emitted by an agricutural sprinkler

5.1.1 <u>Charcterization of the sprinkler radial application pattern</u>

The first step for sprinkler characterization was to obtain the radial application pattern using pluviometer data (Figure 5.1). The resulting pattern is characteristic of impact sprinklers operating at low pressure. It shows low precipitation values (as low as 1.2 mm h^{-1}) at intermediate distances (5-7 m from the sprinkler), and maximum values near the end of the irrigated area. The minimum recorded precipitation was 0.2 mm h^{-1} at 14.0 m from the sprinkler, while the maximum precipitation was 2.8 mm h^{-1} at 11.0 m. The average precipitation along the irrigated radius was 1.6 mm h^{-1}.

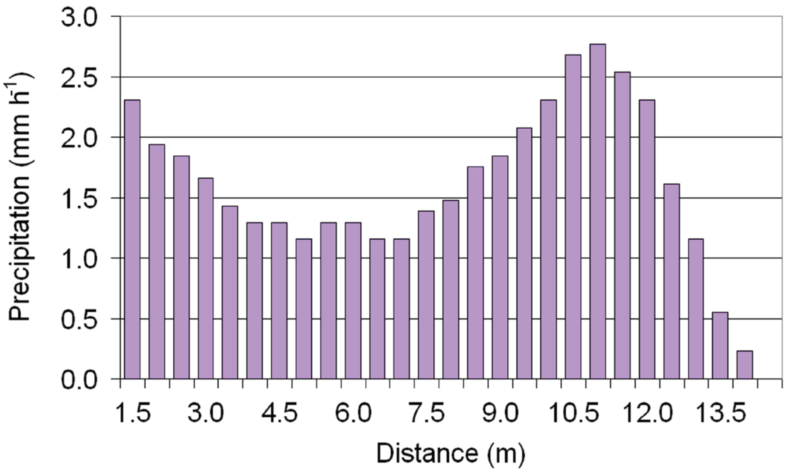


Figure 5.1. Radial application pattern for a VYR35 sprinkler equipped with a 4.8 mm nozzle (including a straightening vane) and operating at a pressure of 200 kPa.

5.1.2 <u>Validation of the proposed photographic method</u>

Photographs taken at distances between the spheres and the vertical plane containing the reference ruler of 0.06 and 0.08 m were out of focus and could not be evaluated. As a consequence, the proposed method characterizes drops located in a range of ± 0.04 m from the focus point (the reference ruler). A total of 43 photographs containing 138 trajectories of the validation metallic spheres (corresponding to the distances to the reference ruler of 0.00, 0.02 and 0.04 m) were evaluated. The average measured sphere diameters were 4.47, 4.59 and 4.60 mm, for respective distances of 0.00, 0.02 and 0.04 m, with respective coefficients of variation of 2.01, 2.74 and 3.13 %. The increase in diameter with decreased distance to the target reflects the error derived from spheres which appear larger than they are because they are closer to the objective. In the worst case, spheres with a real diameter of 4.49 mm resulted in estimated diameters of 4.60 mm. As a consequence, the proposed method results in a maximum average error of $\pm$ 2.45 % at a distance of 0.04 m from the reference ruler. Under a random fall of spheres, the errors produced on both sides of the reference ruler cancel, and the average error can be approximated by the average diameter error at a distance of 0.00 m (-0.45 %). These maximum and average error figures are moderate, and can be compared to the manufacturing coefficient of variation of the spheres ($\pm$0.69 %).

Regarding drop velocity, the average simulated velocity was 3.26 m s^{-1}. The average measured velocities were 3.27, 3.28 and 3.22 m s^{-1} at 0.00, 0.02 and 0.04 m from the reference ruler respectively. The expected average error corresponds to the error at 0.00 m (0.31 %), while the maximum average error was 1.23 % at a distance of 0.04 m from the ruler. In the case of sphere velocity, however, photographic measurements were compared to simulation results, not to velocity measurements.

Drop angle was not validated, due to the physical nature of its measurement procedure and its independence from the distance to the reference ruler.

5.1.3 Basic drop statistics

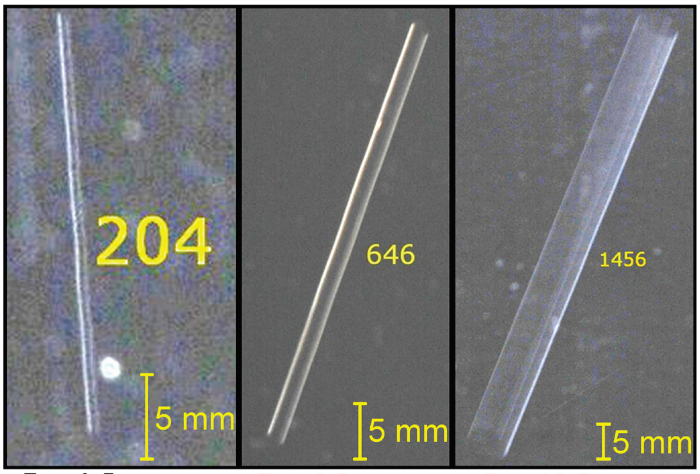
A large number of photographs (about 600) were taken. Only 184 of them contained valid drops. The rest of the photographs were taken before or after the jet passage, or contained very few, unfocused drops. The total number of valid drops was 1,464. Table 5.1 presents basic statistics (mean, minimum and maximum) of the number of drops and the analyzed variables (diameter, velocity and angle) as a function of the distance to the sprinkler. The number of drops ranged from 61 at 12.5 m to 354 at 1.5 m. Average drop diameter increased with distance, with a minimum of 0.6 mm at 1.5 m, and a maximum of

3.3 mm at 12.5 m. Drop velocity also increased with distance, ranging from 1.9 m s^{-1} by the sprinkler to 5.6 m s^{-1} at the limit of irrigated area. Average angle values resulted quite variable, and it was not possible to appreciate a relationship with distance to the sprinkler. In the proximal region the angle was sometimes larger than 90º. This can be attributed to the fact that the experimental setup was located outdoor. As a consequence, turbulences could have distorted drop angle, particularly for small drop diameters. An extended version of Table 5.1, individualizing each drop within each distance from the sprinkler, can be downloaded from www.eead.csic.es/drops.

Table 5.1. Basic statistics of the number of drops and analyzed variables for each distance to the sprinkler.

Distance (m)	Number of Drops	Diameter (mm)			Velocity (m s^{-1})			Angle (º)		
		Average	Min	Max	Average	Min	Max	Average	Min	Max
1.5	**354**	0.6	0.4	1.6	1.9	1.0	3.8	94	65	105
3.0	**205**	0.7	0.5	1.6	2.4	1.4	3.6	70	53	84
4.5	**135**	0.8	0.3	1.8	2.5	0.9	4.1	75	39	112
6.0	**260**	0.9	0.4	2.5	2.5	0.9	5.2	67	43	98
7.5	**156**	1.1	0.4	3.8	3.1	0.9	5.9	88	60	107
9.0	**184**	1.1	0.4	3.1	3.3	1.0	6.3	67	51	86
10.5	**109**	3.0	1.3	6.8	5.6	4.2	7.5	73	61	87
12.5	**61**	3.3	1.7	6.4	5.5	4.2	7.2	69	60	79

Figure 5.2 presents photographs of drops #204, #646 and #1,456. At the bottom of each picture, information is provided on the distance to the sprinkler (D), drop diameter (∅), drop velocity (V) and drop angle (â). To ease visualization, images are presented in different scales. The photographs depict drops as transparent cylinders, and permit accurate, direct determination of their size, even for the smallest diameters. The quality of the photographs permits to obtain the information required to characterize the sprinkler application pattern at any distance. Comparison between the three pictures illustrates the effect of the distance to the sprinkler on drop diameter (increase) and velocity (increase).



D = 1.5 m	D = 4.5 m	D = 12.5 m
∅ = 0.66 mm	∅ = 1.84 mm	∅ = 6.36 mm
V = 1.9 m/s	V = 4.1 m/s	V = 6.4 m/s
â = 94°	â = 71°	â = 68°

Figure 5.2. Typical drop photographs, representative of three drop sizes. The information obtained from drops #204, #646 and #1,456 is presented in the figure (D = Distance to the sprinkler; ∅ = Drop diameter ; V = Drop velocity; and â = Drop angle). A scale bar is presented within each picture.

5.1.4 Drop diameter *vs.* distance

Drop diameter distribution histograms are presented in Fig. 5.3 for all distances to the sprinkler. As the distance to sprinkler increases, the frequency of large drops increases. The smooth transition observed for distances up to 9.0 m becomes abrupt between distances of 9.0 and 10.5 m. These differences could be attributed to the fact that drops landing at distances under 10.5 m from the sprinkler can either be emitted from the nozzle or separate from the jet along its trajectory. This fact could explain the presence of drops with diameters under 1 mm (about 40 % at 9.0 m), which completely disappear at a distance of 10.5 m. From 10.5 m on, all drops seem to result from the disintegration of the jet, and the modal diameters are in the interval 2-4 mm. This hypothesis was presented by Von Bernuth and Giley (1984) and Seginer et al. (1991). Montero et al. (2003) reported similar results when analyzing drop diameter measurements performed with an optical disdrometer. The uncertainties associated to disdrometer measurements, evidenced by Burguete et al. (2007) raised some concern about the quantitative importance of these small drops. Photographic data confirm the relevance of small drops at large distances from the sprinkler, and pose additional concerns about the adequacy of sprinkler irrigation ballistic theory, specifically about the hypothesis stating that all drops are created at the nozzle.

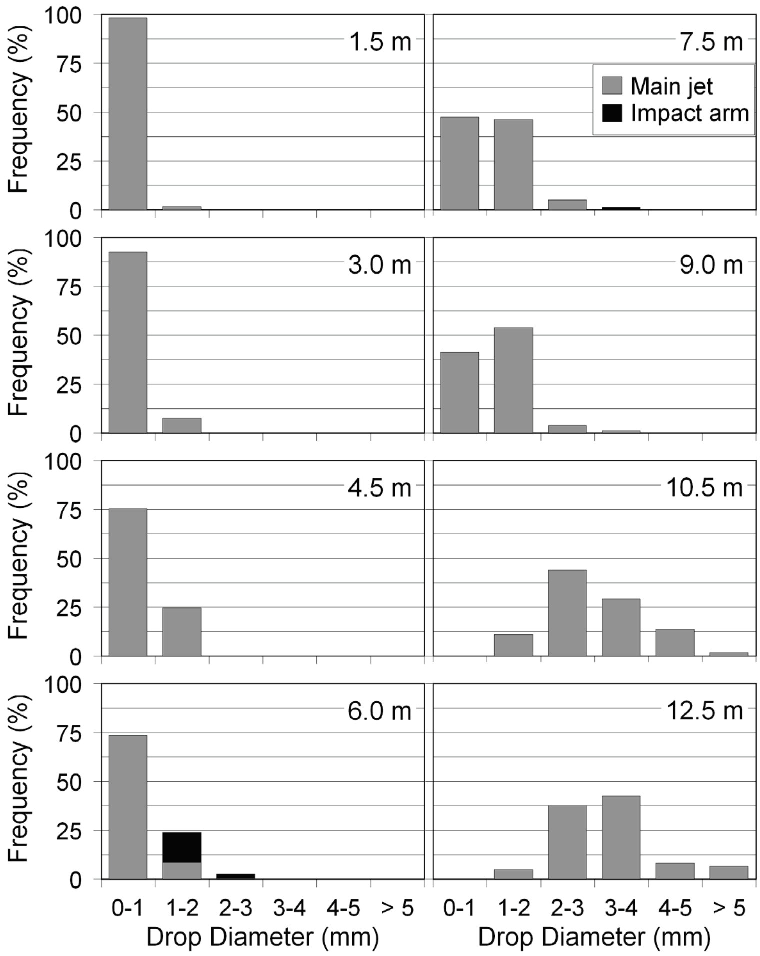


Figure 5.3. Frequency of drop diameter classes at the observation points (distances of 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5 and 12.5 m from the sprinkler). Grey areas represent drops emitted from the main jet, while black areas represent drops emitted by the impact arm.

At distances from the sprinkler of 6.0 and 7.5 m, part of the drops were identified as being created by the oscillations of the impact arm, while the rest of the drops were attributed to the main jet. In Figs. 5.3, 5.4 and 5.5, the frequency of these drops is presented in black columns. Since impact arm and main jet drops were separated in the Figure, it could be observed that impact arm drops were larger than main jet drops at each distance.

Drops under 1 mm constituted the most frequent class for distances up to 7.5 m. The observation distance with the largest frequency of small drops was 1.5 m (98 %). From this distance on, the frequency of small drops decreased as the frequency of large drops increased. The largest diameters (larger than 4 mm) were only present at distances of 10.5 and 12.5 m, and showed frequencies of about 15 %. At a distance of 12.5 m, drops exceeding 5 mm in diameter were more frequent than at 10.5 m, the other distance where they were found.

5.1.5 <u>Drop velocity *vs.* distance</u>

Drop velocity resulted more variable than drop diameter for each considered distance. Figure 5.4 presents the frequency of drop velocity at the observation points. An increase of velocity with distance can be appreciated in the Figure, where three patterns can be observed: 1) Up to a distance of 6 m, velocities were low-medium (up to 5 m s^{-1}). Low velocities (< 3.0 m s^{-1}) prevailed at 1.5 m and at 3.0 m, accommodating about 95 % of the drops in both cases. At distances 4.5 m and 6.0 m, a gradual increase of velocity with distance was evidenced; 2) Between 7.5 and 9.0 m, a nearly homogeneous distribution of velocity could be observed in the range 0-6 m s^{-1}; 3) Finally, for distances 10.5 and 12.5 m, velocities were in the medium-high range (4-6 m s^{-1}). Drops emerging from the impact arm (depicted in black in Fig. 5.4) showed higher velocities than the rest of drops at the same distances. This can be attributed to the abovementioned differences in diameter.

5.1.6 <u>Drop angle vs. distance</u>

Drop angle showed the widest fluctuations among the three analyzed variables (Fig. 5.5). While wind speed was inappreciable during the experiments, turbulences seem to have occasionally influenced drop angle, particularly for the smallest drops. Angles slightly under 90º should be expected, as characteristic of drops reaching the soil surface with a certain component of velocity in the *x* direction. Although most drops show angles in the range 65-95º, the frequency of drops falling with angles in the >95º range is relevant at some distances. The drop diameter pattern (particularly the frequency of small drops) can contribute to explain the variability in drop angle. For distances of 9.0 m and beyond, drops with angles exceeding 85º were practically non-existent (1 % at 9.0 and 10.5 m; 0 % at 12.5 m). Drops landing at these distances were comparatively large and therefore less likely to be affected by turbulences. Drops with angle >85º had a frequency of 96 % at a distance of 1.5 m. This result can be related to the small drop diameter (< 1 mm in 98 % of the drops). Drops with angle >85º also showed a large frequency at 7.5 m (67 %). In the remaining distances, this range of angles was symbolic. Drops with angle 75-85º appeared in very variable frequencies. Drop angles <75º prevailed at larger distances, with frequencies of 83 % at 9.0 m, 75 % at 10.5 m and 98 % at 12.5 m. In the remaining distances, frequencies fluctuated without a clear trend. Drops emerging from the impact arm had lower angles than the rest of the drops at the same distances, with the most frequent class being <65º. While this can be partially attributed to their comparatively large diameter, the action of the arm seems to modify the vertical drop trajectory respect to drops of similar diameter resulting from the main jet.

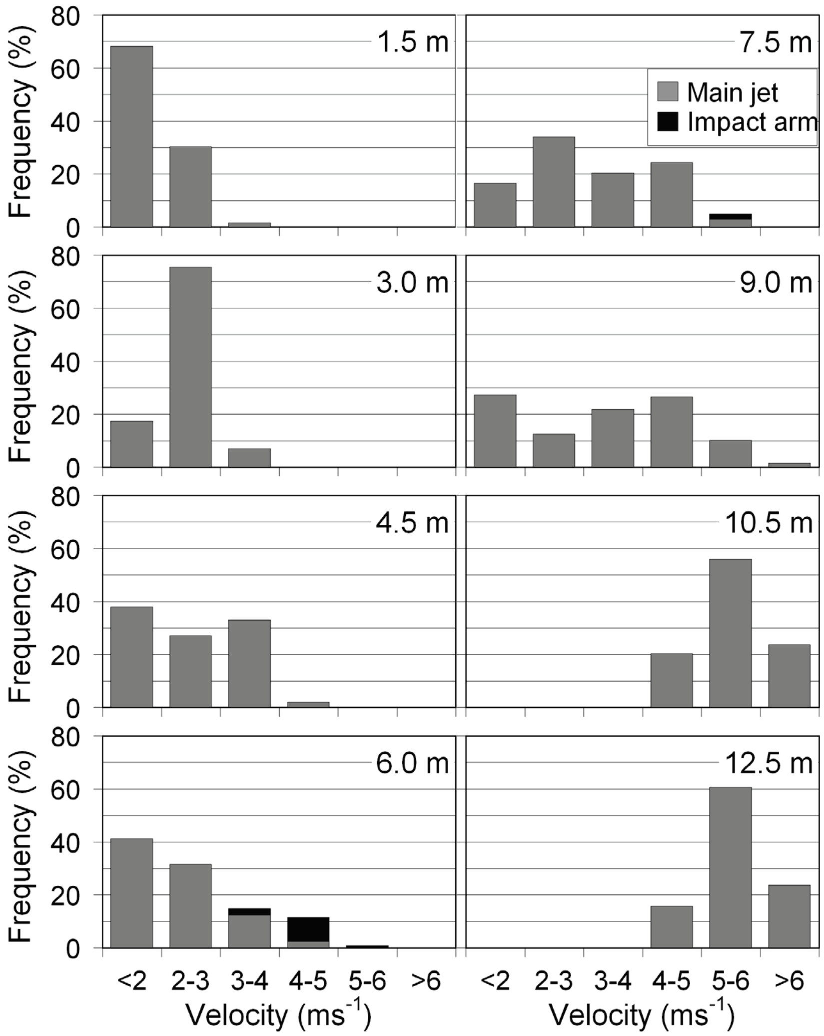


Figure 5.4. Frequency of drop velocity classes at the observation points (distances of 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5 and 12.5 m from the sprinkler). Grey areas represent drops emitted from the main jet, while black areas represent drops emitted by the impact arm.

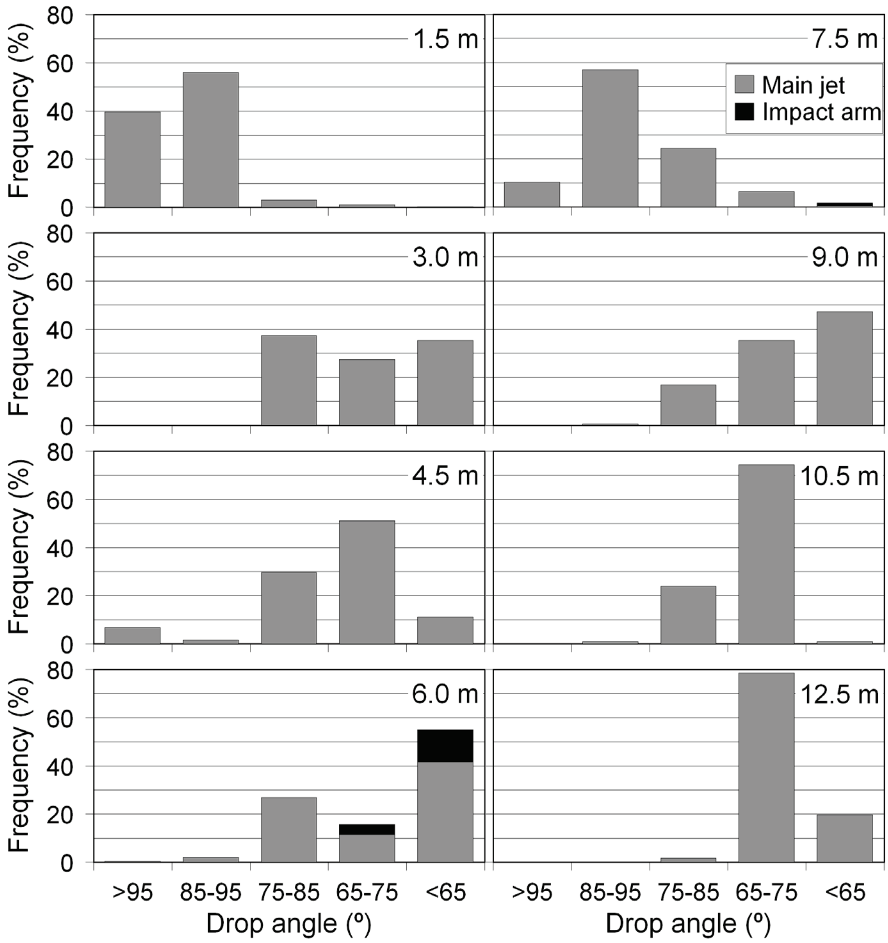


Figure 5.5. Frequency of drop angle classes at the observation points (distances 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5 and 12.5 m). Grey areas represent drops emitted from the main jet, while black areas represent drops emitted by the impact arm.

5.1.7 Cumulative drop frequency and volume

Cumulative drop frequency and volume *vs.* drop diameter are presented in Fig. 5.6 (subfigures 1 and 2, respectively). The graphs show one cumulative line for each observation distance to the sprinkler. Cumulative frequency lines approach 100 % at smaller drop diameters than cumulative volume. This indicates than although the number of large drops is low, their volume contribution is quite large. The cumulative lines corresponding to distances 10.5 and 12.5 m greatly differ from the rest of distances both in frequency and in volume. This can be attributed to the differences in the frequency of large drops (exceeding 3 mm) presented in Fig. 5.3. In the graph presenting cumulative volume (Fig. 5.6.2) curves for distances 6.0, 7.5 and 9.0 appear separated and present less slope than the 1.5, 3.0 and 4.5 m curves. These groups of curves showed a more similar pattern in cumulative frequencies (Fig. 5.6.1).

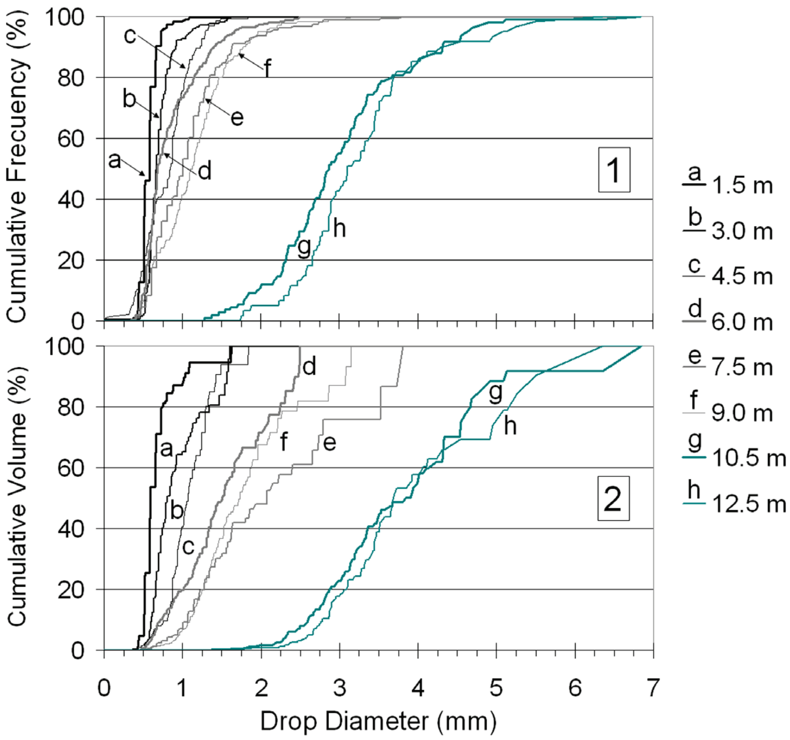


Figure 5.6. Curves of cumulative drop frequency (1) and application volume (2).

The cumulative frequency graph shows that small drops (<2 mm of diameter) exceeded 90 % frequency for distances below 10.5 m, reaching 100 % frequency (and even volume) for distances up to 4.5 m. At medium-large distances the situation changed, particularly in volume. At 6.0, 7.5 and 9.0 m the cumulative volume for small drops was 70 %, 50 % and 65 %, respectively. At the largest distances, 10.5 and at 12.5 m, the curves were less steep both in frequency and volume, indicating that the distribution of diameters was well graded. The volume of small drops (< 2 mm) was 1.5 % at 10.5 m and 0.7 % at 12.5 m.

The drop diameter range 2-5 mm was not important in terms of frequency at medium distances (4.5 to 9.0 m), averaging 5 %. However, this diameter range represented 40 % of the applied volume. Similar findings could be reported for large drops (>5 mm in diameter) at 10.5 and 12.5 m, since these drops only represented 3 % in frequency but 16 % in volume. Although frequency data are particularly interesting to analyze the validity of the ballistic model, the analysis of cumulative volume produces more insight on the significance of different drop diameter classes.

5.1.8 Relationships between drop diameter, velocity and angle

In the previous paragraphs relationships were described between drop diameter and the other measured variables at each observation distance (Figs. 5.3, 5.4 and 5.5). These descriptions were qualitative, since the variables were grouped in diameter ranges and separated by distance to the sprinkler. Figures 5.7 and 5.8 present scatter plots between drop diameter on one hand and velocity and angle on the other, for all characterized drops.

A clear trend was observed between diameter and velocity (Fig. 5.7), which was represented by a logarithmic model (R^2 = 0.91). This trend represents a varying proportionality. The continuous decrease in slope is related to the relationship between drop diameter and aerodynamic drag, and to the fact that small drops are observed in their final, quasi vertical trajectory, while larger drops are usually observed when their trajectory still has a relevant horizontal component. Symbols in Fig. 5.7 represent the observation distance, and reveal that large drops are indeed observed at distal points, while finer drops can be observed at any point, but more frequently near the nozzle.

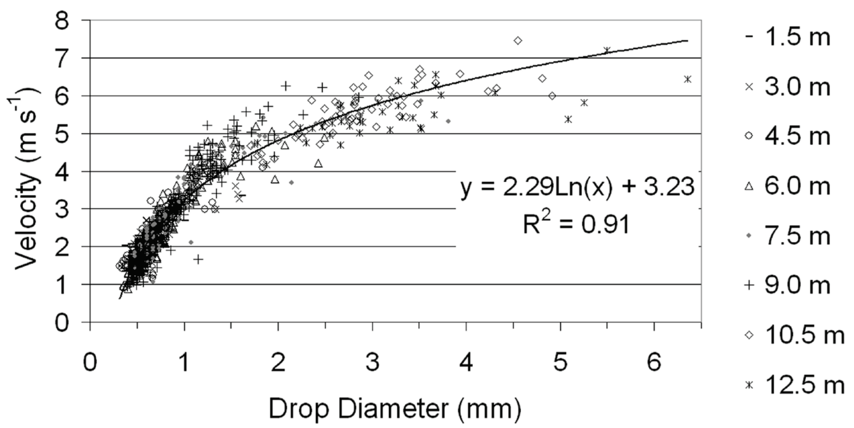


Figure 5.7. Relationship between drop diameter and drop velocity. Each observation distance was represented with a different symbol.

Figure 5.8 presents the relationship between drop diameter and drop angle. The Figure shows an important variability in angle for small drop diameters. The trajectory of small drops was occasionally affected by turbulences distorting their vertical angle. Variability sharply decreased with drop diameter. A significant linear relationship ($p < 0.001$) could be established between both variables, although the coefficient of determination was very low. The application of the linear model to the estimation of drop angle for diameters of 0.5 and 5.0 mm resulted in angles of 80.1° and 59.1°, respectively. As a consequence, a range of 20º in drop angle should be observed in the absence of turbulences in all drop diameters and for all observation points, with the most vertical trajectories corresponding to small drops.

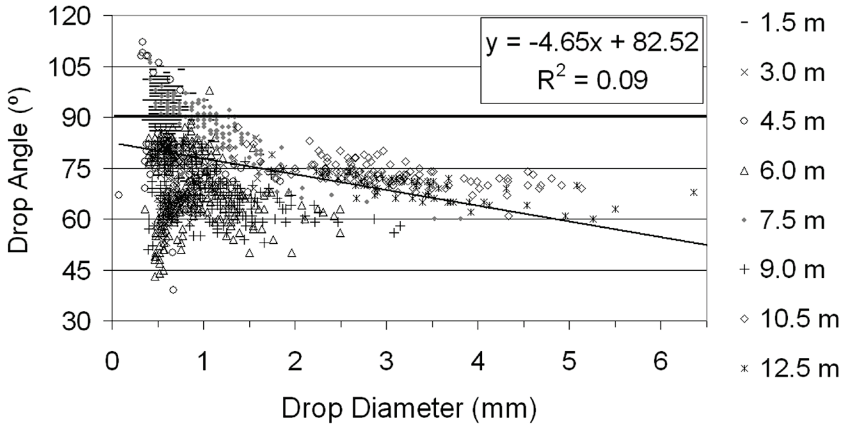


Figure 5.8. Relationship between drop diameter and drop angle. Each observation distance was represented with a different symbol.

5.1.9 Volumetric analysis of drop diameter and velocity

Figure 5.9 presents the cumulative volume applied by each drop diameter class as a function of distance. An increase in the slope of cumulative volume lines was observed as drop diameter increased. This suggests that large drops contribute to sprinkler irrigation in a comparatively narrow circular crown. On the contrary, small drops contribute to the irrigation of wide circular crowns. 80 % of the volume applied by drops with diameter < 1 mm fell between 0 and 6.0 m from the sprinkler, while 100 % fell between 0 and 9.0 m. At this last distance, drops with diameter of 1-2 mm had also applied practically all their volume. On the other hand, drops with diameter ranges 2-3 mm and 3-4 mm applied 63 %

and 86 % (respectively) of their volume between 9.0 and 12.5 m to the sprinkler. Between these two distances, the largest drop class (> 4 mm) applied 100 % of their volume.

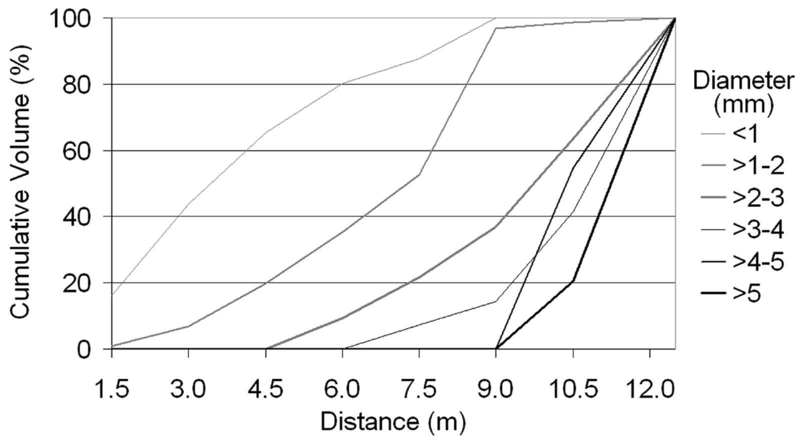


Figure 5.9. Cumulative volume applied by each drop diameter class as a function of distance to the nozzle. Data are presented for different drop diameter classes.

Figure 5.10 presents a visual representation of the results reported in Fig. 5.9. Drops of different diameters are depicted and located in circular crowns centred at the observation points. In this quarter-circle representation, a sample of 500 drops (and half drops) are presented and located in each circular crown following the observed frequencies. The data included in the Figure present the drop distribution in the total area irrigated by the sprinkler in terms of drop frequency and associated volume. Confirming previous results, drop density drastically decreases with distance. At the same time, drop diameter increases and compensates (in terms of volume) the decrease in density. It is interesting to note that 71.6 % of the total drops had diameters <1 mm, with a volumetric contribution of just 7.9 %. On the other hand, the largest drops (>4 mm) had a frequency of 0.7 %, but their volumetric contribution was 27.1 %.

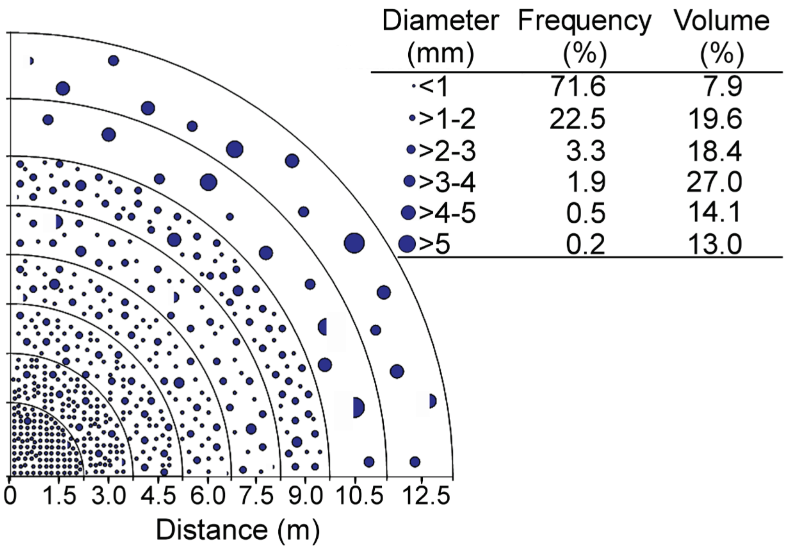


Figure 5.10. Representation of drop distribution resulting from the experimental sprinkler in a quarter-circle. A total of 500 drops (and half drops) are distributed at different distances from the nozzle.

Finally, Figure 5.11 presents the arithmetic (Table 5.1) and volume weighed average drop velocity as a function of distance to the sprinkler. The volumetric average shows an approximately linear relationship between 2 and 6 m s^{-1}, while the arithmetic average reports on a sharp increase in drop velocity between 9.0 and 10.5 m from the sprinkler.

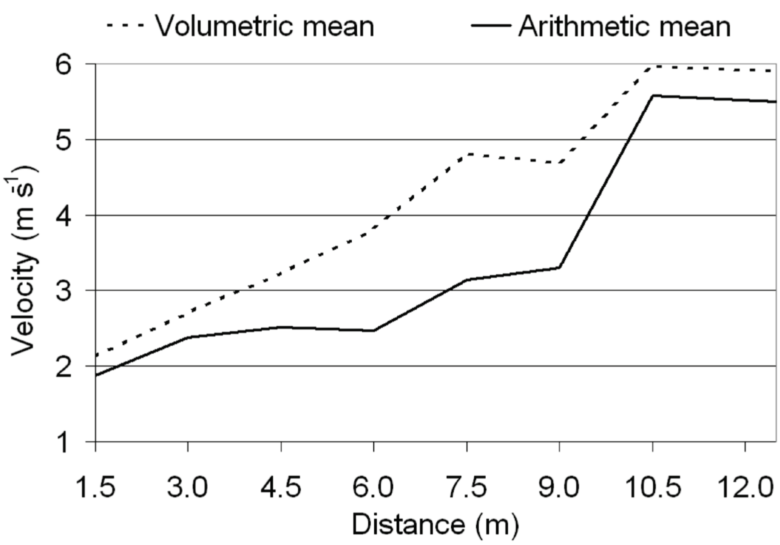


Figure 5.11. Arithmetic and volume weighed average drop velocity as a function of distance to the sprinkler.

5.1.10 Evaluation of the proposed photographic methodology

The proposed method permits direct, visual measurement of the drop variables. It produces quality measurements of the photographed drop population. Photographic data quality is based on the individualization of the drops and on the physical nature of the geometric determinations. Additionally, the proposed technique is low-cost, easy to setup and transport (just a camera and a screen), does not require computing power in the field and permits to measure drop angles. Finally, the proposed technique obtains three variables per drop, as compared to the diameter measurements reported in the literature for optical methods (Kincaid, 1996; Montero et al., 2003).

Unfortunately, the method requires skilful operation in the field and time-consuming processing at the office. About 200 h of work were required to run the field and office phases of the reported experiments. Most of the time (about 7 min drop^{-1}) was devoted to the estimation of drop variables from the treated images. As a consequence, the proposed method results cumbersome and time consuming. Automation of this process could be addressed using image processing, although the initial programming effort could be much more intense than the reported experimentation effort.

5.2. Irrigation scheduling in pressurized networks: the human factor

5.2.1 Exploratory statistics: irrigators, plot size and operation time

The data selection process focused on selecting combinations of year-hydrant presenting high data quality. As a consequence, both the number of hydrants and the area under study differed from year to year. The study areas were 2,736, 2,083, 1,919, 2,788 and 861 ha for 2004, 2005, 2006, 2007 and 2008, respectively (Table 5.2). The irrigation systems installed in the analysed plots included solid-set, drip, pivot and combinations of pivot and solid-set. Considering the area irrigated in each of the study years, the average of area occupied by solid-set was 54 %. Combinations of pivot and solid-set occupied an average 34 % of the area. Pivot irrigation occupied an average 4 % of the area, and the remaining 8 % was occupied by drip irrigation.

Summer field crops were very important in the irrigation district. Corn and alfalfa occupied an average of 46 and 24 % of the studied area, respectively. A certain association could be observed between crops and irrigation systems. This was particularly true in corn, alfalfa and peach trees. Solid-set was installed in 61 % of the corn plots, while in alfalfa 54 % of the area was irrigated by pivot irrigation or combinations of pivot and solid-set. All the area cultivated to peach trees used drip irrigation.

The number of irrigators analysed in each study year averaged 71, ranging from 44 in 2008 to 88 in 2004. The average irrigated area (all study years) was 28.1 ha per irrigator, with a maximum of 32.8 ha per irrigator in 2007 and a minimum of 19.6 ha per irrigator in 2008. The average duration of the irrigation events was 23 hours. This is the time the hydrant is open in each irrigation event. This time is typically very different from the actual irrigation application time in the field, due to the division of the field area into sequentially-irrigated shifts or to the passage time of the pivot. Relevant differences were found in the average irrigation time between irrigation systems: 50 hours for pivots, 36 hours for pivot + solid-set, 23 hours for solid-sets and 11 hours for drip systems.

Table 5.2. Distribution of main crops and irrigation systems in the Candasnos Irrigation District during the stud years. Two crops are often grown in rotation in one year.

		Year				
Irrigation system	**Crop**	**2004**	**2005**	**2006**	**2007**	**2008**
	Alfalfa	368	287	242	211	68
	Barley/Wheat	10	43	200	132	40
	Barley/Corn	140	7	126	214	27
Solid set	**Corn**	819	698	406	744	297
	Snap/Beans	53	39	61	39	52
	Other	59	0	90	99	7
	TOTAL	**1449**	**1074**	**1124**	**1439**	**491**
Drip	**Peach trees**	176	99	98	221	110
	TOTAL	**176**	**99**	**98**	**221**	**110**
	Alfalfa	50	50	0	50	0
Pivot	**Barley**	0	0	0	0	65
	Corn	0	27	65	65	0
	TOTAL	**50**	**77**	**65**	**115**	**65**
	Alfalfa	345	342	332	202	53
	Barley	0	27	23	0	0
	Barley/Corn	92	40	83	164	0
Pivot(s) + Solid set	**Corn**	422	425	193	589	142
	Snap/Bean	179	0	0	58	0
	Other	23	0	0	0	0
	TOTAL	**1061**	**834**	**632**	**1013**	**195**

The starting irrigation time presented two periods of high frequency, located around 8 and 20 hours (Fig. 5.12). 24 % of the irrigation events started between 07:00 and 09:00, while 30 % started between 19:00 and 21:00. These periods defined two trends: daytime irrigation and nighttime irrigation. Other less-frequent times for irrigation start were between 02:00 and 05:00 and between 13:00 and 15:00, representing central hours of the day and night periods.

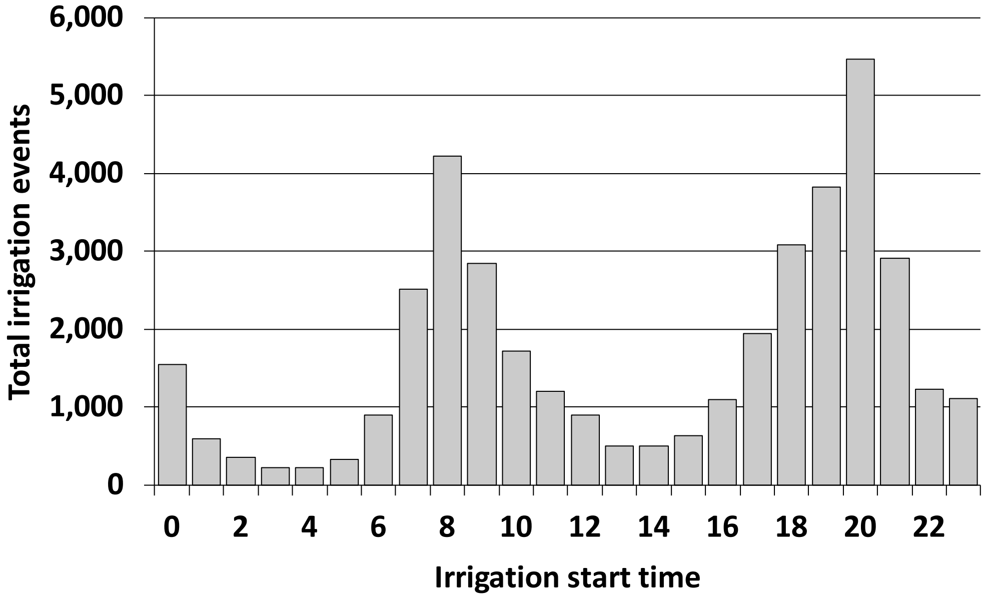


Figure 5.12. Histogram of starting irrigation time (hour) for all events in 2004-2008.

Irrigation hours were grouped in ranges of three hours and separated by months (Table 5.3). In this Table, the two peaks presented in Fig. 5.12 can be identified, but the effect of the season can be observed: during the irrigation season (May to September), the most frequent range of irrigation start time was 18:00 to 21:00. Irrigators are thus aware of the advantages of night-time irrigation. The second frequent range of irrigation start during the irrigation season was 6:00 to 9:00. During the off-season months, the most common starting irrigation time range was 09:00 to 12:00, although a different pattern could be observed in April and November.

During the months of the irrigation season, 35,152 irrigation events were applied. This represents 88 % of the studied irrigations and a monthly average of 7,030 irrigations. In the rest of months irrigation was much less frequent, with an average of 680 irrigations per month, and a total of 4,757 irrigations.

Table 5.3. Monthly percentage of irrigation events starting at different time ranges, The most frequent monthly time range is presented in bold type.

	Month											
Start time range	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0 - 3	0.7	1.0	2.9	7.3	6.6	8.2	6.8	5.2	4.5	4.4	0.0	7.7
3 - 6	1.5	2.5	1.8	1.7	1.3	2.2	2.6	1.6	1.8	2.2	0.0	0.0
6 - 9	9.0	15.8	20.9	24.4	21.0	19.9	16.5	17.6	20.9	19.2	0.0	10.8
9 - 12	53.0	36.9	32.8	23.6	13.3	12.3	10.8	11.6	17.2	27.2	0.0	49.2
12 - 15	11.2	20.7	13.2	5.8	4.9	4.0	4.0	4.5	3.6	6.4	60.0	18.5
15 - 18	14.2	16.7	16.2	11.6	10.0	8.5	9.2	8.3	7.3	7.1	20.0	9.2
18 - 21	6.0	5.4	10.2	17.2	27.1	29.6	35.9	37.4	33.7	26.3	20.0	4.6
21 - 0	4.5	1.0	2.0	8.4	16.0	15.2	14.2	13.7	10.9	7.3	0.0	0.0

Regarding the percentage of irrigation hours in daytime or nighttime, all months within the irrigation season exceeded 50 % of nighttime irrigation. The month with the highest percentage of nighttime irrigation hours was July, with 58.3 %. Out of the complete irrigation season, the percentage of daytime irrigation hours was about 70 %.

Figure 5.13 presents the number of hydrants simultaneously irrigating during each semi hourly value and for each year of study. Since differences among study years in the number of considered hydrants were high, data were standardized dividing by the yearly average of hydrants simultaneously irrigating. A clear decrease in hydrant operation could be observed at the central hours of the day, reaching minimum values between 16:00 and 17:00. Hydrant operation increased along the evening, typically reaching a peak in the early hours of the night (21:00 - 2:00). These results differ from previous findings by Khadra and Lamaddalena (2010) in southern Italy. Peak irrigation flows were recorded at the central hours of the day (from 9:00 to 17:00). In that study, crops included olive trees and vegetable crops, generally under drip irrigation. Differences in the irrigation system explains the opposite daily water use patterns in both areas, since drip irrigation performance is independent of meteorology.

In 2005 irrigation water was limited due to water shortage at the system main reservoirs. Irrigators were more careful about water application, giving preference to the nighttime hours (Fig. 5.13). Irrigator behavior in this year resulted in the largest differences between number of hydrants irrigating between daytime hours and nighttime hours. This pattern cannot be explained by differences in evapotranspiration and precipitation at the irrigation district during the irrigation season. In fact, 2005 was an intermediate meteorological year in comparison with the rest of analysed irrigation seasons.

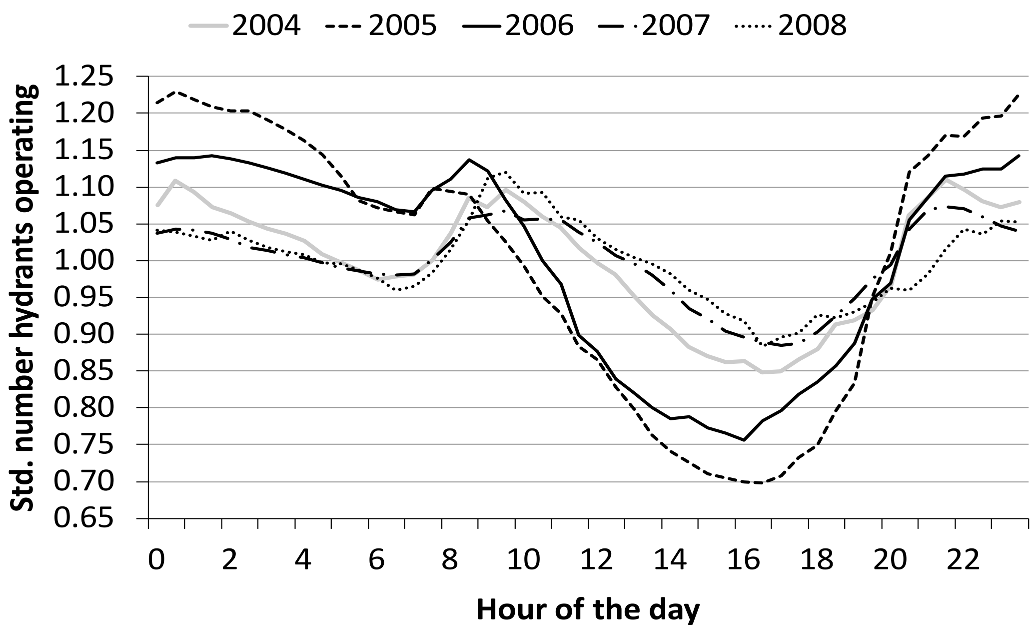
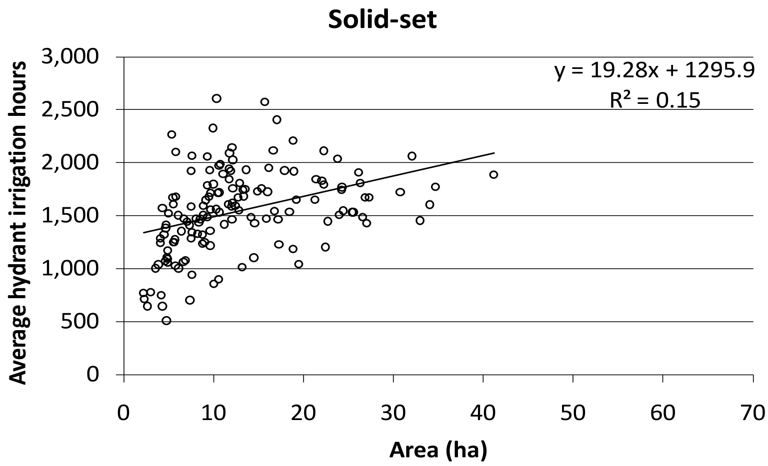


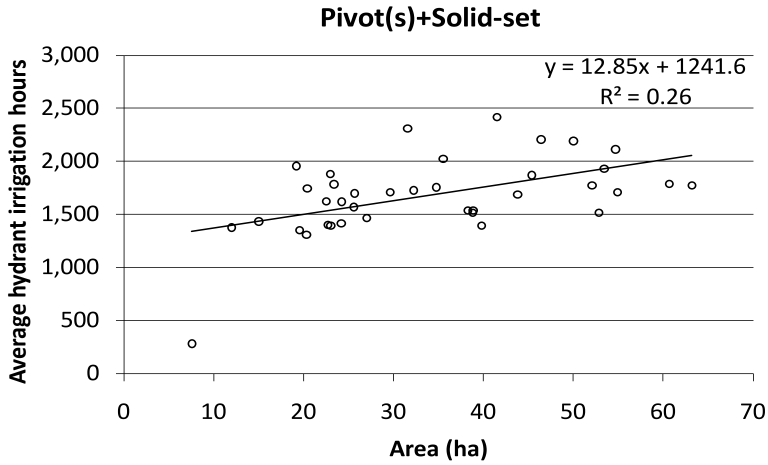
Figure 5.13. Standardized number of operating hydrants (divided by the average number of operating hydrants of each year) vs. time within the day (hour). Data are presented for 2004-2008.

Figure 5.14 presents the relationship between the plot area and the average yearly hydrant irrigation hours. Data are presented for different irrigation systems. The scatter plot for solid-sets presents a weak but significant relationship (R^2=0.15). The variability in irrigation hours is influenced by the variability in hydrant discharge and on-farm design for the same plot size, but it basically reveals differences in individual irrigation management. It is interesting to note that the variability is severely reduced with increasing plot size. In the case of pivot and pivot + solid-set, a better relationship could be appreciated. This seems to be due to the fact that irrigation management in pivots is easier than in solid-sets. Similarities could be appreciated between both irrigation systems: the regression intercept is about 1,300 hours and the slope is 19 in solid set and 13 in pivot(s) + solid-set. Finally, a significant relationship between plot area and irrigation hours could not be established in drip irrigation. Dechmi et al. (2003b), in a study about an irrigation district in northeast of Spain, reported a significant and negative relationship between the plot area and the applied irrigation water depth. The differences between that study and the present results can be attributed to different water costs and agricultural systems.

5.2.2 Meteorology and irrigation

In order to assess the influence of meteorology on irrigation scheduling, semi-hourly and daily values were analysed in conjunction with the number of simultaneously operating hydrants at a given time. As an example, Figure 5.15 presents daily precipitation and the daily number of hydrants in operation during 2005 and 2006. A decrease in hydrant operation was detected in both years following medium to large precipitation events (exceeding about 10 mm). Despite the oscillations in hydrant operation introduced by a number of additional factors, the effect of precipitation on irrigation scheduling is clear but moderate: precipitation only occasionally reduces irrigation operation to less than half.





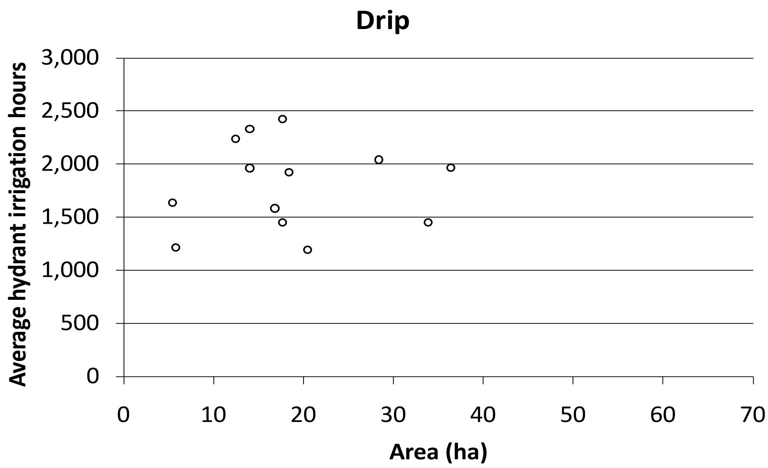


Figure 5.14. Number of yearly irrigation hours vs. irrigated area for the hydrants irrigating three types of irrigation systems: solid-.set, pivot + solid-set and drip.

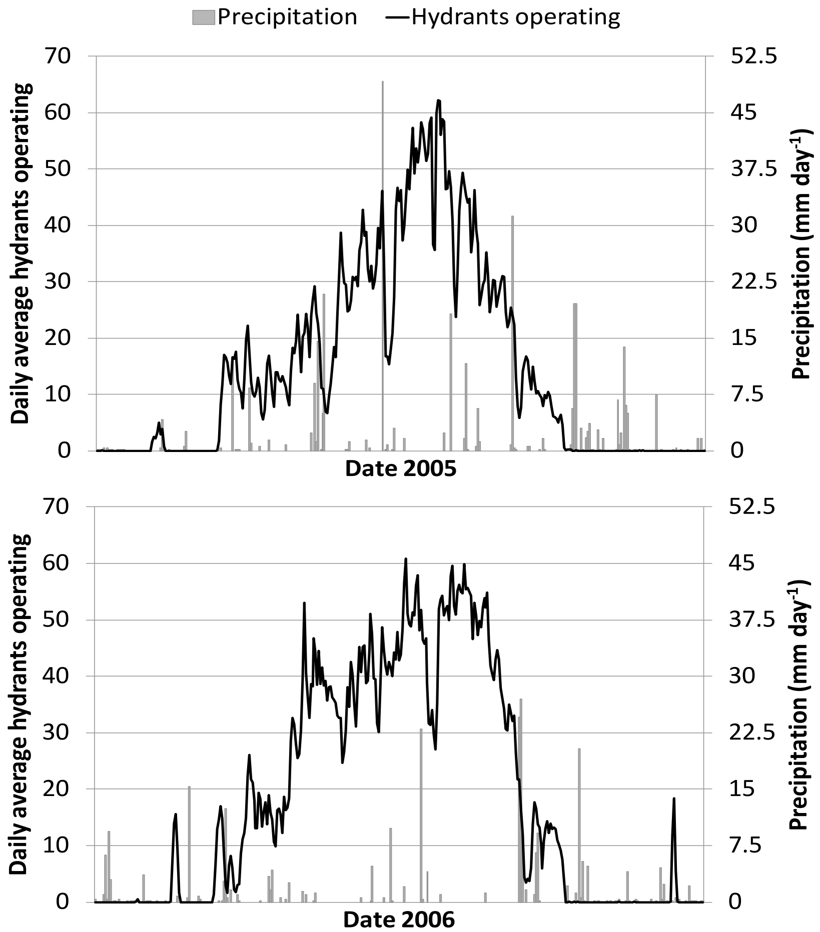


Figure 5.15. Yearly evolution of the number of hydrants operating in a given day and daily precipitation. Results are presented for 2005 and 2006.

The effect of wind speed, temperature and relative humidity on sprinkler irrigation scheduling was analysed using semi-hourly values and only for hydrants with solid-set or pivot + solid-set. Non-parametric correlations were used, determining Spearman's Rho (r_S). Regarding wind speed, monthly correlation analyses were performed from May to September (25 analyses in total). 84 % of these analyses were significant ($P<0.01$) and showed a negative correlation coefficient. The average value of significant coefficients was -0.285, ranging between -0.113 and -0.552. Similar analyses were performed for temperature and relative humidity. Results were more variable. Significant, negative correlations were found in 60 % of the analysed months for air temperature (average r_s of -0.469). Regarding relative humidity, 84 % of r_s coefficients were significant and positive (average of 0.418). The influence of wind speed, relative humidity and air temperature on sprinkler irrigation has been analysed in a number of research works. In the local conditions, Playán et al. (2005) reported a clear relationship between these variables and wind drift and evaporation water losses. Ortiz et al. (2009) experimenting in a different area of semiarid Spain, reported similar results, emphasizing the influence of the wind speed. Finally, Tarjuelo et al (1999) reported on the influence of wind speed on irrigation uniformity.

A certain trend was observed to schedule irrigation during times when meteorology is adequate for sprinkler irrigation performance. However, in a detailed hydrant analysis, this trend could not be identified. The lack of immediate reaction to meteorology is determined by the fact that farmers order their irrigation water two days in advance, and can not cancel their water orders following a sudden change in meteorology. As a consequence, meteorological effects should show a minimum two-days delay.

5.2.3 Classification of irrigation patterns

Cluster hierarchical analyses resulted in a total of ten groups of irrigation patterns (labelled A to I). Each of them contained a different number of elements (hydrant-years). Groups were differentiated when separated by more than 6 re-scaled units. Identified groups belong to two hierarchical families. The first one includes groups A to D, while the second includes groups E to I. The distance between both families is 25 re-scaled units. Distances within groups in a given family are variable, ranging between the 5 units separating groups E and F, and the 18 points separating group I from the rest of the second family. Figure 5.16 presents a scheme of the characteristics of each group in terms of irrigation starting time and number of weekly irrigations. Table 5.4 presents the number of hydrant-year combinations in each cluster group.

In the first family, group A starts irrigation during the morning (6:00 - 12:00). On the average, 1.9 irrigations are applied every week (SD = 1.0 irrigations/week). In group B irrigations often start between 0:00 and 3:00, averaging 2.3 irrigations/week (SD = 1.3 irrigations/week). Group C starts irrigation at the same time as group B, but shows 5.2 irrigations/week (SD = 2.3 irrigations/week). Group D often starts at the same range as group A, but shows more and more variable number of irrigations (average of 5.2 irrigations/week, SD = 2.3 irrigations/week).

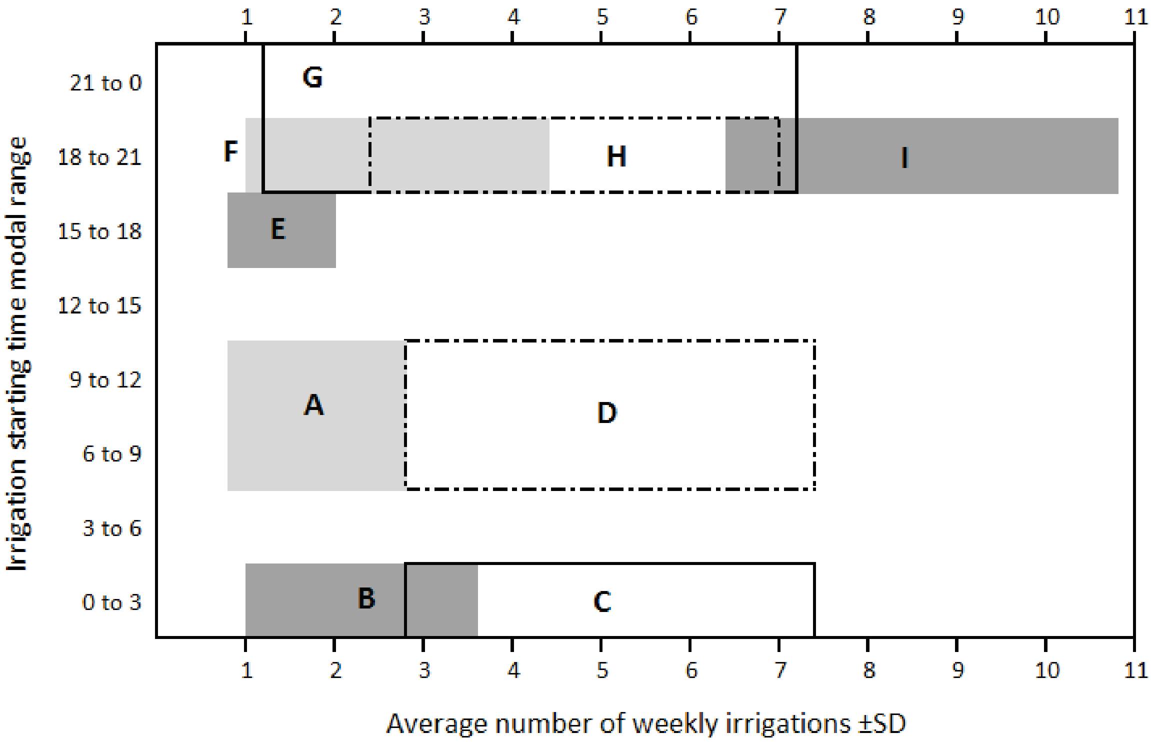


Figure 5.16. Graphical representation of the attributes of the different irrigation scheduling groups: number of weekly irrigations and irrigation starting time.

In the second family, group E shows the lowest number of weekly irrigations (on the average, 1.4 irrigations/week, SD = 0.6 irrigations/week). This is the only group starting in the afternoon-evening (15:00 - 18:00). Groups F, H and I start irrigating a bit later (18:00 - 21:00), but show differences in irrigation frequency. Group F is characterized by 2.6 irrigations/week, while groups H and I reach 4.6 and 7.6 irrigations/week, respectively. Regarding the standard deviations, values are 1.6, 2.2 and 3.2 irrigations/week for groups F, H and I, respectively. Finally, group G is similar to H in terms of number of weekly irrigations, but shows a larger variability (SD = 3.0 irrigations/week), and starts irrigating from 18:00 to 0.00.

Cluster hierarchical analyses have been applied before to agricultural irrigation studies (Karami, 2006). However, this author used the technique for a different purpose: identifying the adequacy of a given irrigation system. Categorical regression was performed to assess the influence of additional variables in the definition of irrigation pattern groups. Significant variables included the irrigator, with an importance of 56.4 %, the irrigation system (32.9 %), and the crop (10.7 %). The adjusted regression coefficient was 0.736. The irrigation year, the plot size and the maximum hydrant discharge per unit plot area were not statistically significant.

Table 5.4 shows the distribution of cluster groups by crop and by irrigation system. Clear associations could be observed between irrigation systems and cluster groups. This is particularly true for pivot(s)+solid-set with group A (54 % of records) and for drip with group D (89 % of records). Group H is very common in solid-sets (42 % of records), although group A occupies 23 % of the records. Group F is quite uniformly distributed across most irrigation systems. Some of these associations stem from the characteristics of the irrigation systems. For instance, long irrigation events are required in pivot irrigation.

Some associations could also be observed between crops and groups. Group A (long, low-frequency irrigations) represented 56 and 41 % of records in Alfalfa and barley, respectively. Group H (frequent irrigations starting at sunset) led the classification in corn, barley/corn and snap/bean. Finally, cluster D (frequent irrigations starting during the morning) capitalized peach trees. Again group F was populated by different crops.

5.2.4 Irrigation patterns, irrigators, irrigation systems and crops

Six examples of irrigation patterns are presented in Figure 5.17 to illustrate the variability in irrigators' behavior. Subfigures a) and b) present the same hydrant (and irrigator) in different crops and years. Despite the fact that the crops (alfalfa and corn) differ in cropping techniques and irrigation management, group A was assigned to both cases. The main difference between then was the duration of the irrigation events, which in corn were uninterrupted along the peak of the irrigation season. In alfalfa, irrigation was interrupted during hay harvest operations. Subfigures c) and d) present similar traits as subfigures a) and b) (same irrigator, same irrigation system, different crops). However, the irrigation patterns resulted different: H for subfigure c) and B for subfigure d). The irrigator applied different irrigation scheduling patterns to both crops, giving long irrigations to alfalfa and short, frequent irrigations to corn. These differences are not explained by differences in crop water requirements, and derive from the individual preferences of the irrigator. Finally, the last pair of subfigures (e and f) correspond to two different irrigators. The crop (peach trees) and the irrigation system (drip) are the same in both graphs. Irrigation scheduling patterns were classified in groups D and I for graphs e) and f), respectively. Two management strategies are presented for fruit trees, both with frequent irrigations starting during the daytime. Lamacq (1997) presented a similar effort of graphing irrigation scheduling. Her purpose was to validate a simulation model for irrigation scheduling, not for to classify irrigation behavioral patterns.

Table 5.4. Frequency of the different irrigation scheduling groups in the main crops and in the different irrigation systems. Frequencies over 20 % are presented in bold type.

Group Elements	163	36	10	57	9	95	7	194	5
GROUP	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
CROP									
Alfalfa	**56**	9	0	4	4	15	1	10	1
Barley	**41**	12	0	2	0	**27**	0	17	0
Barley/Corn	11	2	4	2	0	**24**	2	**54**	0
Corn	18	5	3	6	0	17	2	**48**	1
Peach tree	0	0	0	**89**	0	0	0	5	5
Snap/Bean	**22**	6	0	6	0	**28**	0	**39**	0
IRRIGATION SYSTEM									
Solid-set	**23**	7	2	4	2	17	1	**42**	1
Drip	0	0	0	**89**	0	0	0	5	5
Pívot	**83**	0	0	0	0	17	0	0	0
Pívot(s) + Solid-set	**50**	3	0	5	1	**22**	1	17	0

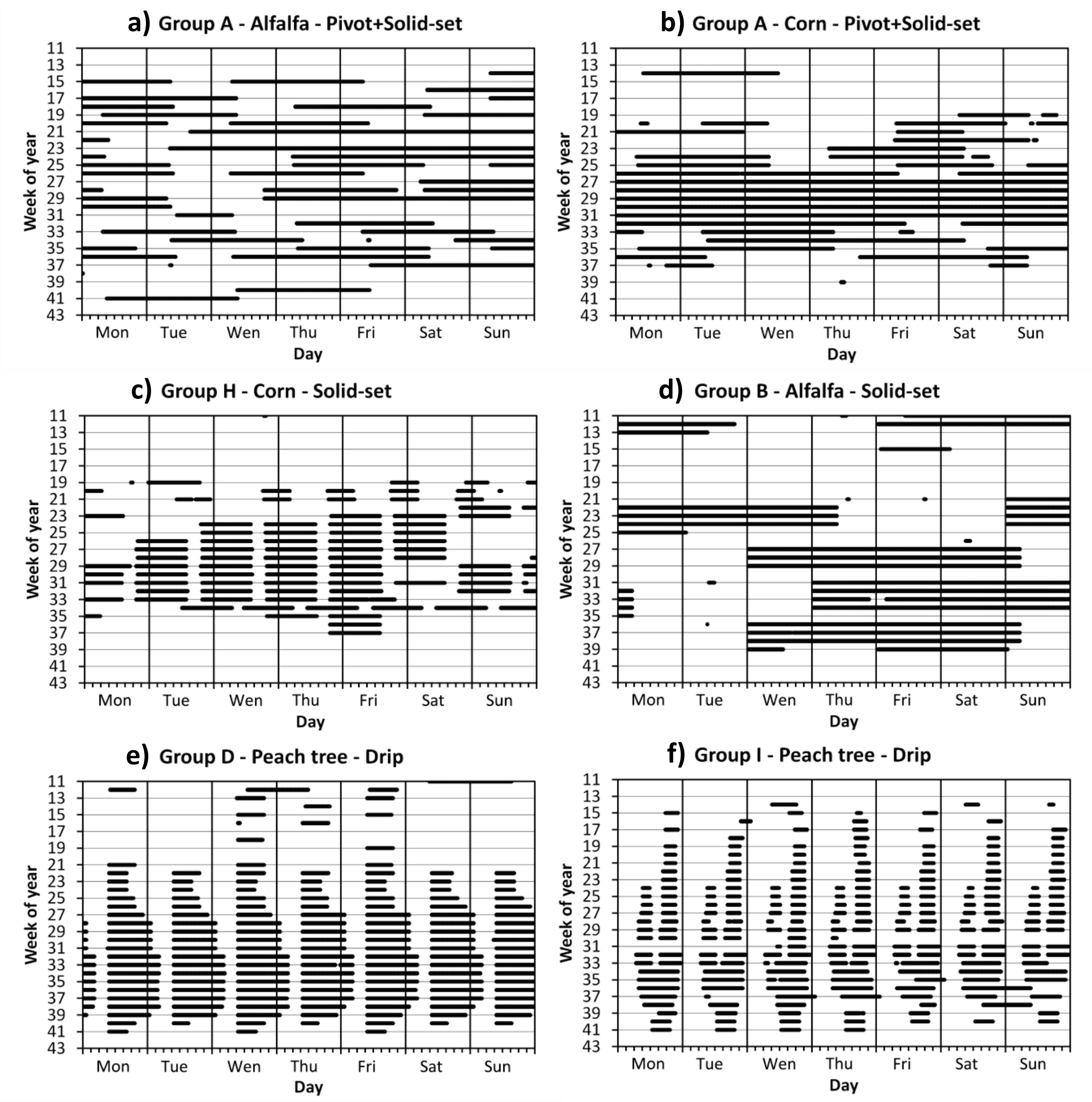


Figure 5.17. Representation of six irrigation schedules involving different irrigation scheduling groups, crops and irrigation systems. The black line indicates hydrant in operation.

An analysis was run on the inter-year variability of irrigator's behavior for all the plots with the same irrigation system. Figure 5.18 – illustrating this analysis – is again divided in six subfigures. Subfigure a) typifies the irrigator who gets all hydrants classified in the same group. This is the case of 34 % of irrigators, although only half of them (17 %) irrigated more than one hydrant-year. Most drip irrigation farmers showed this behavior, since group D is clearly prevalent in this irrigation system. Subfigure (b) typifies an irrigator that generally followed a given irrigation pattern, but showed an atypical pattern in a given year. No trend in the irrigation schedule pattern can be appreciated in this case. This trait could only be observed in 5 % of the analyzed irrigators. Subfigures c), d) and e) show a certain time trend. Subfigures c) and d) belong to the same irrigator, but differ in the irrigation system. A certain pattern is observed in the first years of the study, with evolution along the years. In fact, in 2008 (subfigure c) or 2007 and 2008 (subfigures d e), the group(s) stabilized. 22 % of the analyzed irrigators presented a certain evolution in their irrigation patterns along the irrigation system. Finally, subfigure f) presents the most common type of irrigators' behavior, with 39 % of the analyzed population. Changes in the group of irrigation pattern are common and do not follow appreciable trends.

In the last group analysis, the goal was to assess the irrigation pattern groups applied by each farmer to his crops. All hydrant-years for each farmer were analyzed per group and crop (Figure 5.19). Subfigure a) uses different groups for the same crop (four, in this case) along the study years. 20 % of the irrigators followed this behavior. Subfigure b) presents a case typifying an opposite behavior: irrigators' irrigation pattern is classified in the same group in all occurrences of the same crop. This behavior could be observed in 21 % of the irrigators, but only 4 % of the irrigators in this group had more than one occurrence of the same crop. Subfigure c) typifies crop specialization, with each crop being classified in the same group. Only 14 % of the analyzed irrigators belonged to this category. Subfigure d) shows an opposite behavior to c): all crops are classified in the same group. 8 % of the farmers showed this low-profile irrigation pattern. The remaining 37 % of irrigators were typified in the last category, illustrated by subfigures e) and f). In this case, at least 50 % of the hydrant-year-crops are classified in the same group, while the rest populates other irrigation pattern groups. The prevalence of groups d), e) and f) (45 % in total) underline the relevance of the irrigator in the irrigation pattern, as announced by the categorical regression analysis.

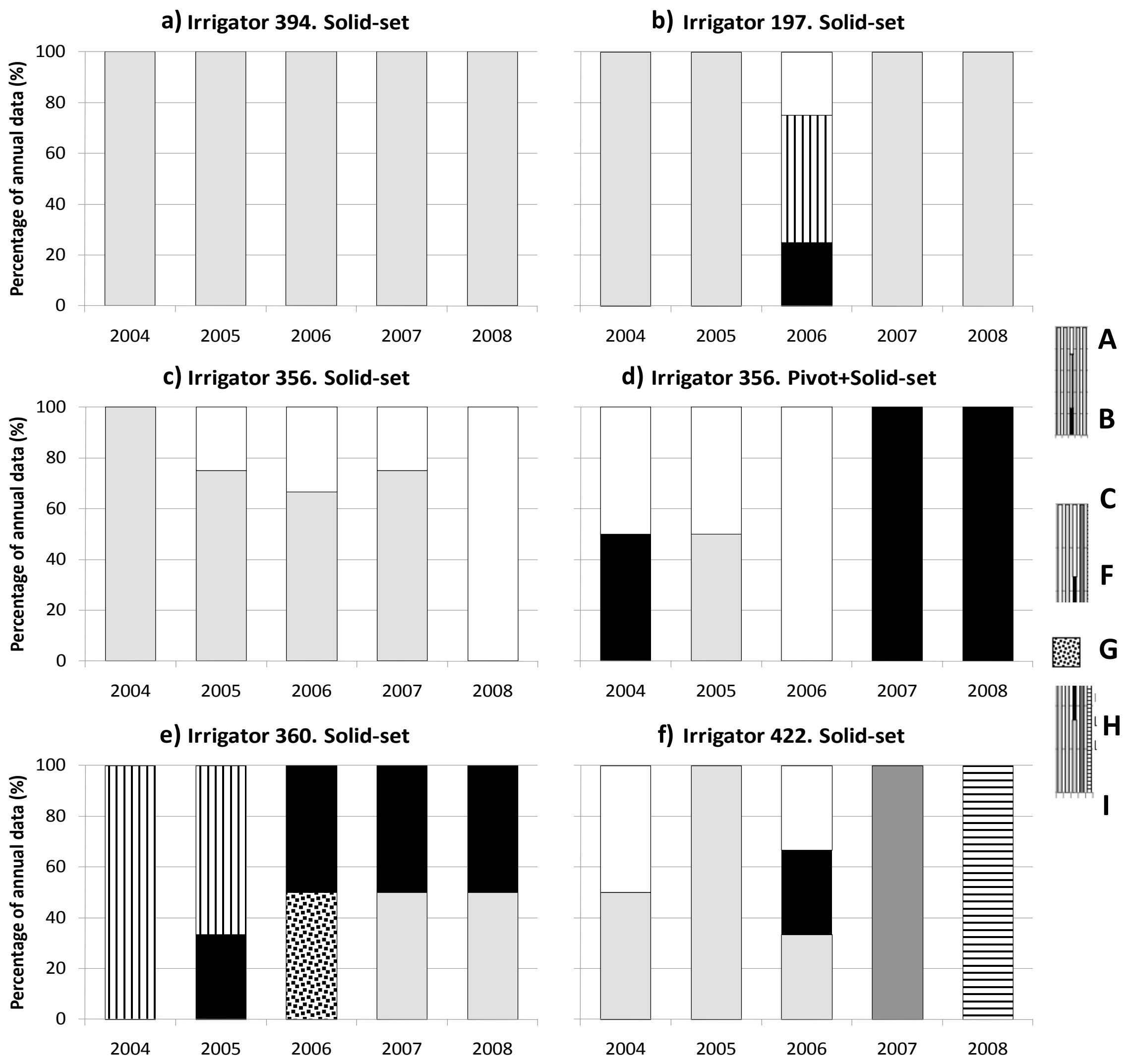


Figure 5.18. Irrigator adoption of different irrigation scheduling groups along the years of study. Subfigures correspond to combinations of irrigator and irrigation system. Different crops can be considered within each subplot.

The results above can be connected to the findings of Zapata et al. (2009). These authors analysed sprinkler irrigation scheduling in a similar, adjacent irrigation district. They focused on irrigation adequacy, and concluded that the farmers' irrigation scheduling practices limited the yield of field crops. They proposed a collective irrigation controller as a means to better adapt irrigation water application to crop water requirements and to the changing environment. The results of this research point to the same direction. In fact, many different irrigation scheduling patterns have been identified. Farmers use them in a non-specialized way, and show inconsistencies their application in time and different crops and irrigation systems. Since the RSCS has long been installed in the analysed district, the opportunity arises to use it to distribute centrally elaborated irrigation schedules focusing on water conservation and on farmers' economic return. This research ha not addressed any of these issues, but has revealed frequent lack of consistency and specialization in irrigation scheduling patterns.

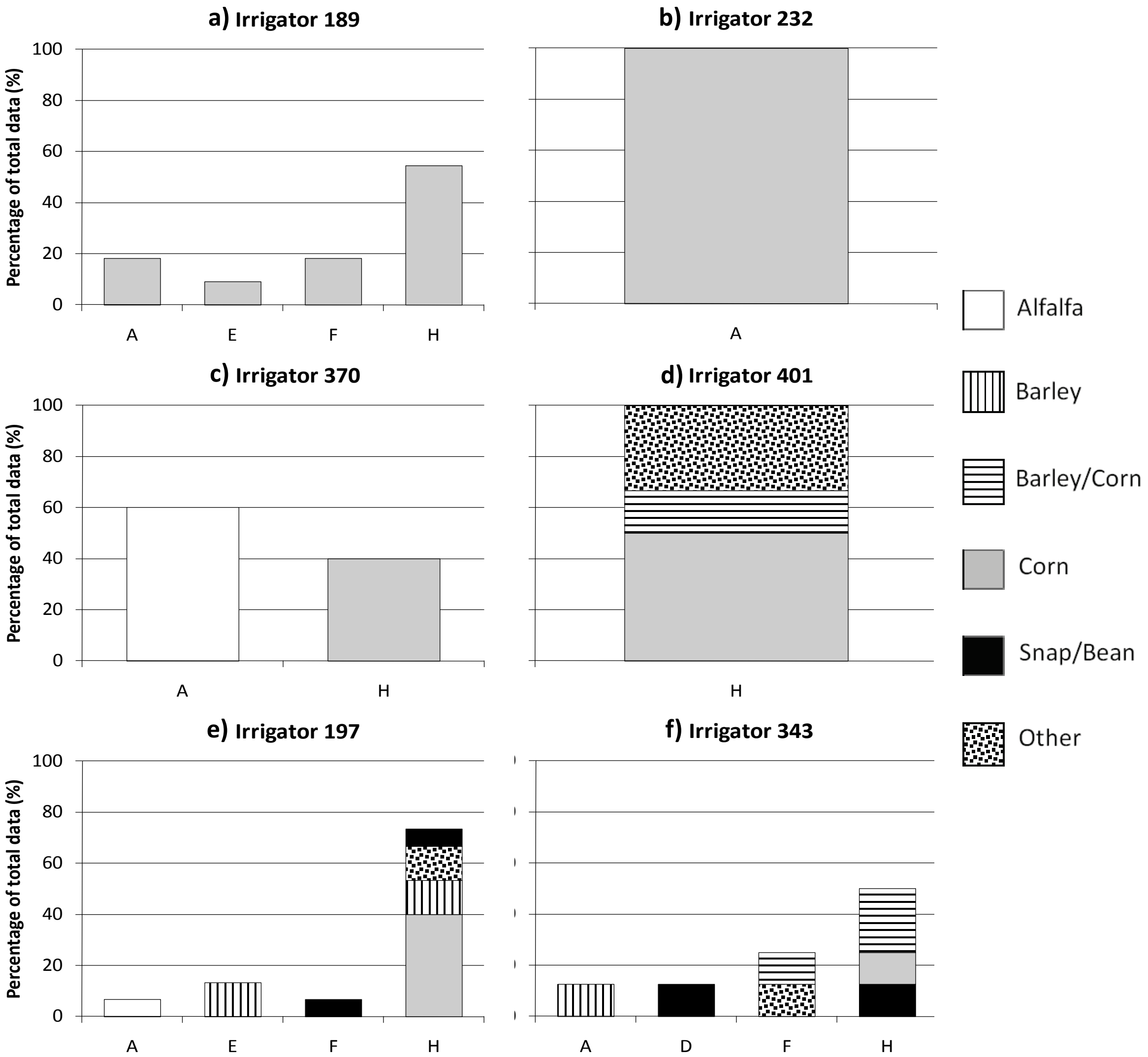


Figure 5.19. Irrigator attitude towards the different irrigation scheduling groups. Subfigures present how a given irrigator distributes his crops among the different groups. All hydrants irrigation systems and years are considered in this analysis.

5.3. Irrigation performance in urban environments.

5.3.1 Household landscape areas

The initial database contained 134 households. In a first analysis of water records and aerial photographs, a total of 32 households were discarded due to the absence of landscape, zero landscape water use or presence of a swimming-pool. These last households were discarded because the type and volume of water used to supply the swimming-pools was unknown.

The size of the landscape areas ranged between 25 and 222 m^2, with an average of 93 m^2. This type of landscaping is smaller than the one used in previous studies located in the USA, in which areas as large as 500 m^2 (Devitt et al., 2008) or 1,000 m^2 (Aquacraft-Inc, 2003; Haley et al., 2007) were reported. In a residential area located in Barcelona (Spain), Domene and Saurí (2006) analysed landscapes with areas similar to this study: 83 % of the landscapes were smaller than 100 m^2.

The most common interval of landscape area in Montecanal was 60-80 m^2, including 25 % of the analysed households (Fig. 5.20a). 69 % of the landscape areas fell in the interval of 60-120 m^2. The percentage of landscape area to household area ranged between 9 and 60 %, with an average value of 34 %. The landscape area allocated to turf was on the average 60 m^2 (Fig. 5.20b). This average value included extreme values such as households without turf and a household with 195 m^2 of turf area. Turf area represented from 8 to 100 % of the landscape area, being the most common range 65-75 %. 77 % of the households had more than 50 % of its landscape area covered with turf, while 31 % of them used turf in more than 75 % of the landscape area. Similar turf ratios were previously described in the USA (Aquacraft-Inc, 2003; Haley et al., 2007) and in Barcelona, Spain (Domene and Saurí, 2006). In areas where water is scarce or expensive, turf ratios tend to be low (St.-Hilaire et al., 2008). In these cases, turf is replaced by species showing lower water requirements. A significant correlation ($P<0.01$) was found in this study between landscape and turf areas, with Spearman's Rho coefficient (r_s) of 0.724. The relationship between landscape area and turf ratio was not significant. These results suggest that landowners in Montecanal are not restricted by water availability or cost in the planning of their landscape area.

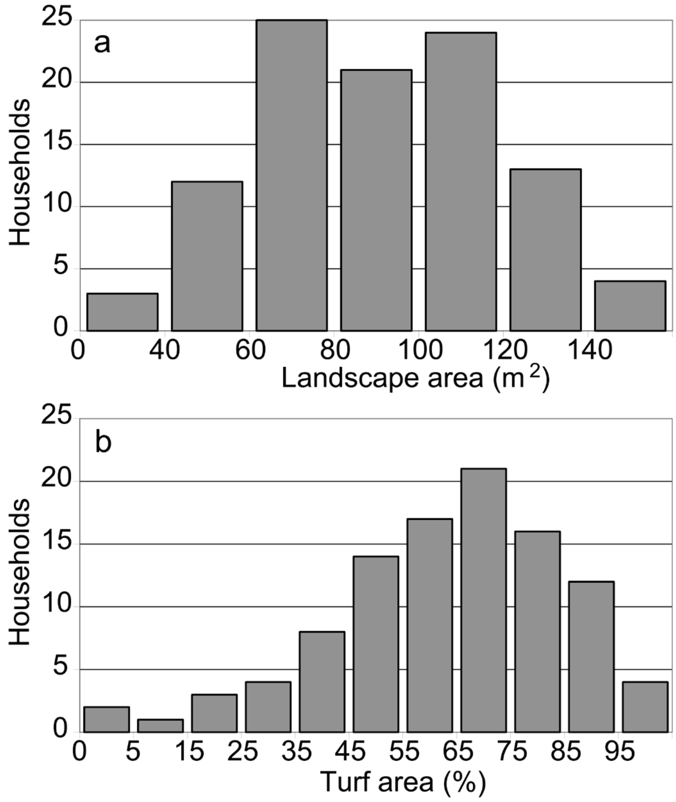


Figure 5.20. Histograms of landscape area (a) and turf area (b) in Montecanal.

5.3.2 Water use

Figure 5.21 presents the total water volume used in the 102 studied households, separating indoor and landscape irrigation water. A clear seasonal effect could be observed on total water use. In the three years of study, total water use trends were very similar. The period with largest water use was Jul-Aug, with an average of 7,046 m^3 (for a two-month period). The second was May-Jun (with an average of 6,275 m^3), followed by Sep-Oct (5,033 m^3) and Mar-Apr (4,131 m^3). In winter periods only indoor water was used, with an average of 2,678 m^3. Regarding total water use per household and day, a value of 0.80 m^3 household per day was obtained, similar to that presented by Moreno et al. (2007) for households located in Madrid, Spain (0.60 m^3 $household^{-1}$ day^{-1}).

Irrigation water represented 46 % of the total annual water use in Montecanal. This value is consistent with values reported in the literature (in general, between 30 to 66 %) and is similar to the values reported by Hunt et al. (2001) in California and Loh and Coghlan (2003) in Western Australia, (46 and 56 %, respectively). During the irrigation season, the ratio of irrigation to total water was maximum in Jul-Aug (69 %), and minimum in Mar-Apr (38 %).

Figure 5.21 also shows that the variability in irrigation water use is much higher than the variability in indoor water use, confirming the observations by White et al. (2004) and Moreno et al. (2007). The two main characteristics of household irrigation water (high volume and high seasonal variability) make the use of two separate distribution networks a very adequate solution. A positive correlation between total water use and irrigation water use was found (r_S = 0.775; $P<0.01$). This correlation was also found by Vickers (2001).

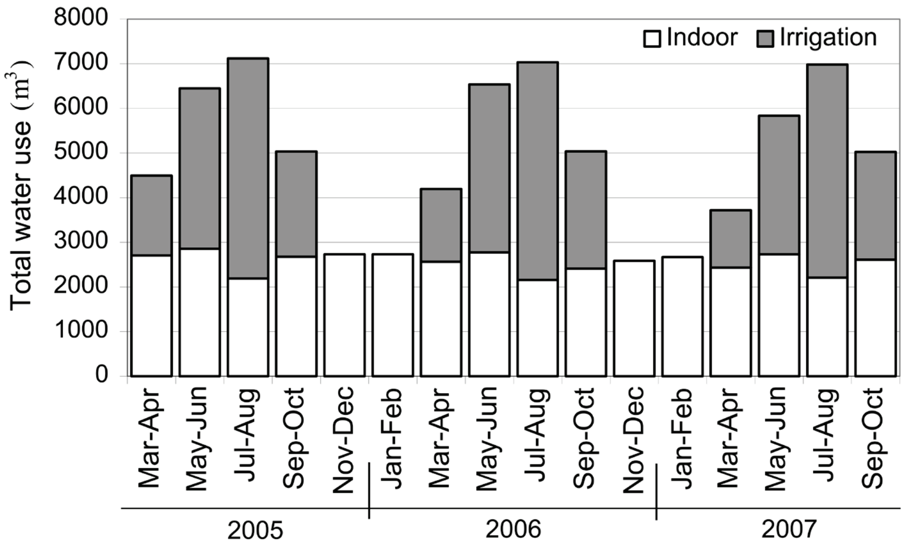


Figure 5.21. Total water use, separating indoor and irrigation water.

The average use of indoor water amounted to 25.1 m^3 per household in a two-month period, corresponding to 0.50 m^3 household^{-1} day $^{-1}$ (Fig. 5.22a). Loh and Coghlan (2003) reported a similar value of 0.42 m^3 household^{-1} day^{-1}. The standard deviation of bi-monthly indoor water use was similar in all seasons and presented high values, with an average of 12.3 m^3. Some seasonality could be observed in indoor water use, with maxima in May-Jun

(27.3 m^3) and minima in Jul-Aug (21.4 m^3). This seasonality in indoor water use is related to the local holiday habits, and was reported by Moreno et al. (2007), while in Australia, Loh and Coghlan (2003) did not find any time variability.

The average bi-monthly indoor water use in winter months was 26.3 m^3, 4.8 % higher than the average of 25.1 m^3. Several authors (Syme et al., 2004; White et al., 2004; Endter-Wada et al., 2008) proposed to estimate indoor water use as the difference between total water use and indoor water consumption in winter, assuming that all winter water consumption is performed indoor. The dual water records used in Montecanal permitted testing of this hypothesis, to conclude that the method would have systematically underestimated outdoor water use in Jul-Aug, the period with highest irrigation requirements, by 23 %. As a consequence, a local study of yearly indoor water use seems to be required before adopting the hypothesis of constant indoor water use.

Figure 5.22b presents bi-monthly irrigation water use, expressed in depth units. The irrigation trends were similar in the three years of study, with maxima in Jul-Aug (average of 532 mm), followed by May-Jun (380 mm), Sep-Oct (279 mm) and Mar-Apr (167 mm). Irrigation system automation is widespread in this type of household developments (Moreno et al., 2007). This explains the peak water use in a period when many houses are not occupied due to summer vacations. The values of water use for the same two-month period in the different years were relatively heterogeneous. Variability among households was quite high, as revealed by the high values of SD.

Moreno et al. (2007) reported that irrigation water use increased with temperature and decreased with precipitation. The comparison of Montecanal water use data and meteorological data (Table 4.2) suggests that users base irrigation scheduling on ambient temperature. The correlation between average temperature and average irrigation water use was significant ($r_s = 0.958$, $P<0.01$). However, the precipitation peaks presented in 2005 (May-Jun), 2006 (Sep-Oct) and 2007 (Mar-Apr) could not be statistically related to a decrease in irrigation water use. Therefore, in general, Montecanal water users did not stop their irrigation systems following intense precipitation events.

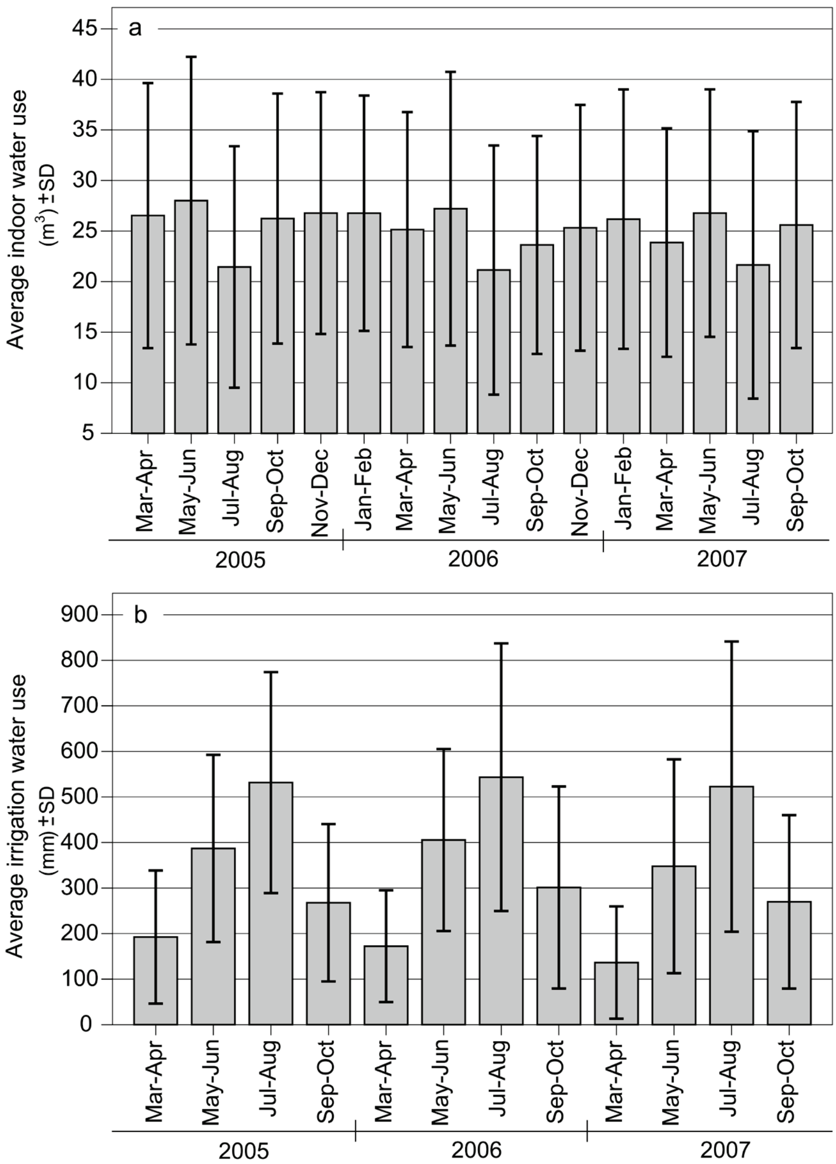


Figure 5.22. Average indoor water use (a) and average irrigation water use (b) from the study periods from the years 2005, 2006 and 2007. Error bars indicate ± standard deviation (SD) among households.

The relationship between landscape and turf areas on one hand and volume of irrigation water use on the other was assessed. Positive, significant correlations ($P<0.01$) were obtained between irrigation water volume and landscape and turf areas (correlation coefficients of 0.450 and 0.307, respectively). Similar relationships were found by Syme et al. (2004), Moreno et al. (2007) and Devitt et al. (2008). A significant correlation could not be found between landscape or turf areas and irrigation water depth (mm). However, negative correlations have been reported between irrigation depth and irrigated area in agricultural irrigation (Clemmens and Dedrick, 1992; Dechmi et al., 2003a).

5.3.3 Irrigation requirements

The species factor (k_s) ranged between 0.55 (all landscape area with trees or shrubs) and 0.82 (all landscape area with turf), with an average of 0.72. In 91 of the 102 households, turf and trees or shrubs shared the landscape area, while in the remaining 11 households soil surface was only occupied by either turf or trees and shrubs.

The average K_L was 0.60, ranging from 0.39 to 0.69. The most common range of values was 0.60-0.64, which included 28 % of Montecanal households. A total of 75 households (74 %) presented K_L values between 0.56 and 0.69. Montecanal K_L resulted somewhat smaller than the values reported in the literature (Kjelgren et al., 2000; Morari and Giardini, 2001; White et al., 2004; Haley et al., 2007 and Endter-Wada et al., 2008), with differences being due to local climatic factors and landscaping preferences. The calculated K_L values were closely related to the percentage of turf in each household. In fact, both variables resulted significantly correlated (r_s = 0.937; P<0.01).

Figure 5.23 presents the net irrigation requirements corresponding to each two-month period. The highest values appeared in summer periods, with Jul-Aug showing the most pronounced peaks (with an average value of 229 mm). The average IR_n in May-Jun was 166 mm. Mar-Apr and Sep-Oct IR_n showed a large variability among the study years. In Mar-Apr, IR_n fluctuated from 19 mm in 2007 to 116 mm in 2005, while in Sep-Oct, IR_n ranged from 42 mm in 2006 to 112 mm in 2007. Among the irrigated periods, minimum IR_n was observed in Mar-Apr 2007 and Sep-Oct 2006, in coincidence with the above mentioned precipitation events (Table 4.2). Among households, IR_n presented much lower variability than IWA. The inter-household variability in IR_n was only due to K_L.

5.3.4 Irrigation performance: comparing IR_n and IWA

Comparison between IR_n and IWA is presented in Table 5.5 for the different study periods. In annual averages, IWA was always higher than IR_n (1,359 and 555 mm for IWA and IR_n, respectively). A clear relationship could not be established between both variables on a yearly basis, suggesting that landowners did not use irrigation water requirements information to schedule irrigation. Inter-household SD values were high for IWA, with an average of 677 mm. The corresponding value for IR_n was 67 mm.

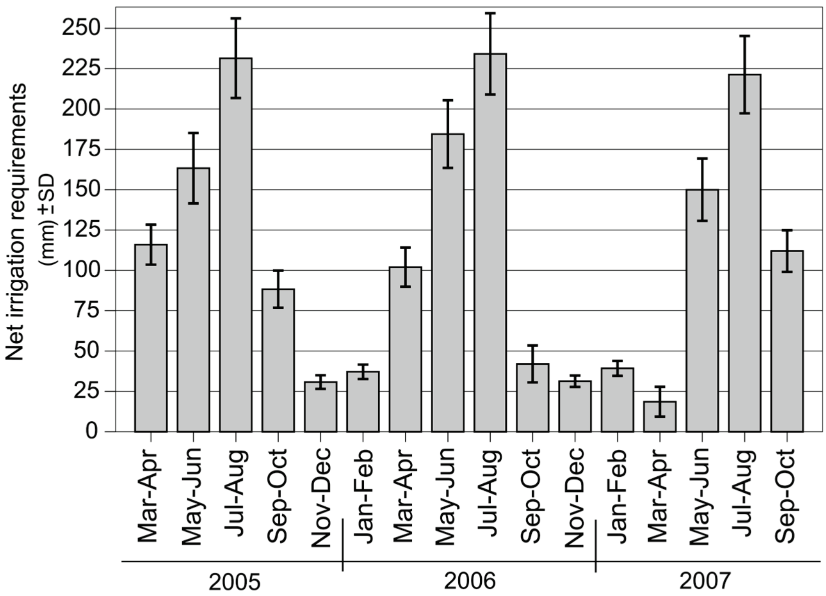


Figure 5.23. Net irrigation requirements (IR_n) for the study periods. Error bars indicate ± standard deviation (SD) among households.

Regarding average bi-monthly data, Mar-Apr and Sep-Oct IR_n were similar, while Sep-Oct IWA was much higher than Mar-Apr IWA. These results further support the trend to overirrigate during Sep-Oct, which was previously described by Kjelgren et al. (2000) and Hunt et al. (2001) for the fall season. Apparently landowners did not react on time to the decrease in water requirements by adjusting their irrigation controllers. For instance, Hunt et al. (2001), reported that 68 % of residential users changed their irrigation schedule a maximum of four times during the year, a number that seems insufficient to ensure proper water use. The large inter-household IWA variability indicates that water application decisions were largely subjective. This issue has been analysed in research works aiming at identifying and modelling the motivations governing household irrigation scheduling decision-making (Domene and Saurí, 2003; Syme et al., 2004; Parés-Franzi et al., 2006 and Endter-Wada et al., 2008).

Table 5.5. Basic statistics of net irrigation requirements (IR_n) and irrigation water applied (IWA) in the study periods.

		IR_n (mm)	SD IR_n (mm)	IWA (mm)	SD IWA (mm)
YEAR	**2005**	599	70	1,378	629
	2006	563	70	1,422	681
	2007	502	65	1,276	722
PERIOD	**Mar-Apr**	79	11	167	131
	May-Jun	166	21	380	213
	Jul-Aug	229	25	532	285
	Sep-Oct	81	12	279	195

A significant correlation could be established between IR_n and IWA, ($r_s = 0.481$, $P<0.01$). When this analysis was performed separately for each household, a significant relationship ($P<0.01$) could only be established for 55 households. In 77 households the relationship could be established with a significance of $P<0.05$. Correlation largely improved when T_m was used instead of IR_n ($r_s = 0.958$, $P<0.01$). When this correlation was analysed in each household, significance at the $P<0.01$ level was observed in 69 households. These results confirm the relevance of average temperature in irrigation decision making.

5.3.5 Irrigation performance classification

In order to classify the analysed households regarding to their irrigation performance, an analysis of hierarchical conglomerates was performed, based on the absolute difference between IWA and IR_n for each two-month period. Four different groups (A, B, C and D) were identified, choosing values of “Rescaled Distance Clusters Combine” higher than 7 units. Group A was further divided in two subgroups (A1 and A2), with a distance between subgroups of 3 units. The number of households was 33, 32, 6, 16 and 10 for groups A1, A2, B, C and D, respectively. A total of 5 households could not be included in any group because the distance separating them to each group was too large. Figure 5.24 presents two types of graphs for each group. Scatter plots (left) use different symbols for each bi-monthly period and two lines: a solid line for the regression equation and a dashed line for the 1:1 line. Bar/line charts (right) present average IWA (in bars ±SD) and IR_n (in lines) for the households included in each group.

Group A1 presented the lowest differences between IWA and IR_n, with an average of 79 mm. Differences were maximum during Jul-Aug, with an average of 115 mm. The average inter household SD was 105 mm. The regression line corresponding to group A1 was the closest to the 1:1 line, with a slope of 1.48 and a coefficient of determination (R^2) of 0.33.

In group A2 linear regression resulted in the highest determination coefficient ($R^2 = 0.53$), although differences between IWA and IR_n amounted to an average value of 223 mm. The slope of the regression line was 2.49, indicating excessive irrigation throughout the year.

Group B includes households in which IR_n was in general higher than IWA. The average difference was -77 mm. In this group (representing 6 % of the classified households), the highest variability among years could be observed. Although in 2005 differences between IWA and IR_n were minimum, in 2006 and 2007 irrigation water application was much lower than IR_n. Apparently, a reduced number of users decided to apply a very small water depth. Irrigation was not suspended during the study period, and maintained some proportionality with landscape water requirements.

Groups C and D showed generalized overirrigation, which was more evident in group D, where the average difference between IWA and IR_n was of 470 (347 mm for group C). In both groups Jul-Aug was the period with highest differences (average values of 508 mm in group C and 658 mm in group D). In group C, the slope of the regression line was of 3.26. Group D was the only one in which the regression intercept was significant, with a value of 330 mm. The regression slope was 2.05.

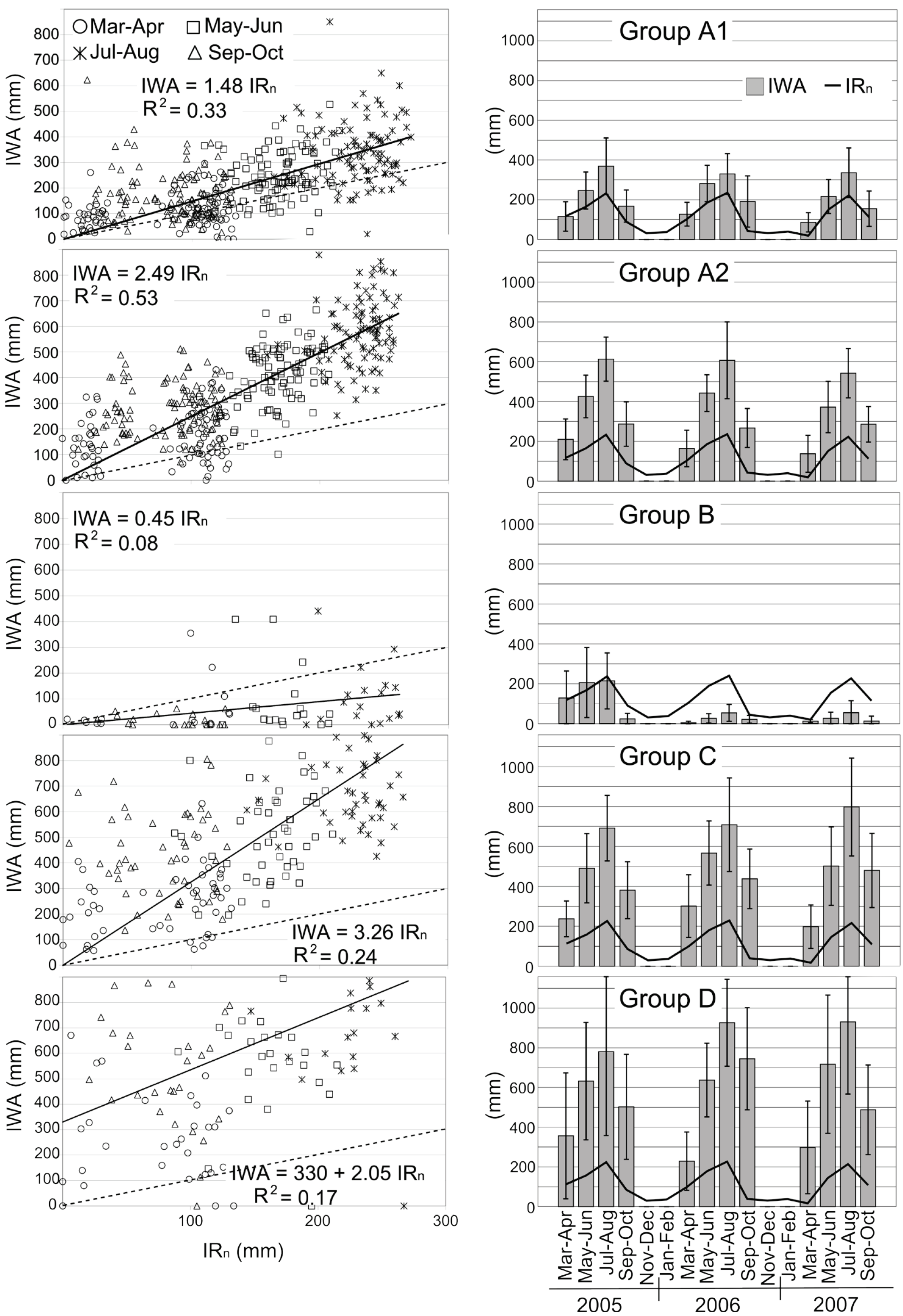


Figure 5.24. Comparison between irrigation water applied (IWA) and net irrigation requirements (IR_n) in each group of households: scatter plots (left) and bar diagrams (right) for each group of households. In the scatter plots, bi-monthly periods are represented by different symbols. Two lines are displayed: a solid line for the regression equation and a dashed line for the 1:1 line. In the bar diagrams, average IWA (in bars ±SD) and IR_n (in lines) are presented.

The average ARIS (all households and irrigation periods) was 2.52, with a SD of 1.39. These values confirm that overirrigation was a common practice in the study area. When the different irrigation years were considered, average ARIS values of 2.37, 2.60 and 2.59 were obtained for 2005, 2006 and 2007, respectively. These values are much larger than those commonly found in agricultural irrigation and higher than values reported in urban landscapes in Barcelona (Parés-Franzi et al. (2006) found that 56 % of public garden were underirrigated) . Agricultural ARIS values are typically lower in water stressed areas or in specific crops such as vineyards, olive tress and sunflower (Lorite et al., 2004). Similar results should be found when analysing water use in private landscapes of water-short cities or planted with drought-resistant species.

Figure 5.25 presents an ARIS histogram for the three years of study. The Figure confirms that about 10 % of the landscapes were systematically underirrigated (a threshold ARIS value of 1.0 was used for this judgement). These households probably correspond to group "B" in the irrigation performance classification. About 25 % of the households exhibited ARIS values between 1.0 and 2.0, an interval that can be said to contain adequately irrigated households. This was the most frequent ARIS interval in 2007, with 27 % of households. The most common range of ARIS values in 2005 and 2006 was 2.0-3.0, representing 45 % of households in 2005 and 32 % in 2006. This range of ARIS values was also a significant portion in 2007, with 26 % of households.

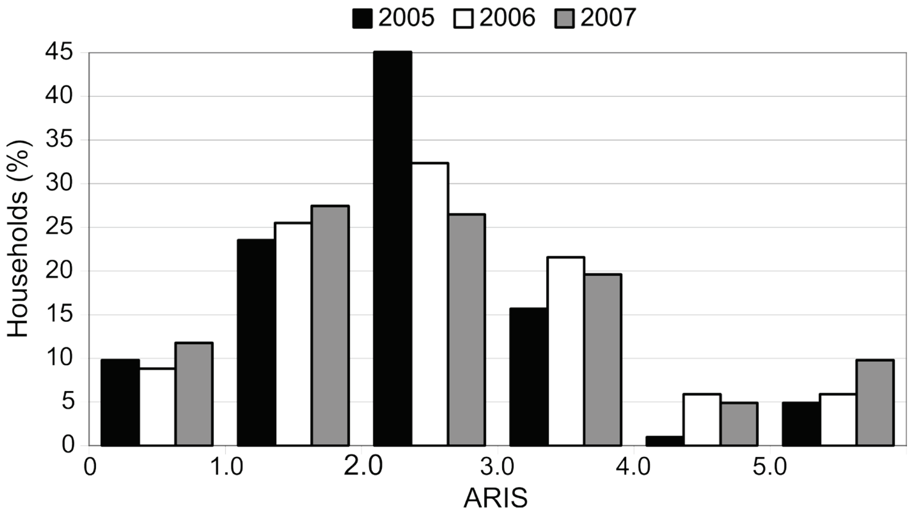


Figure 5.25. ARIS histogram for the study years. ARIS was determined as the ratio of IWA to IR_n.

Significant correlations ($P<0.01$) were found for ARIS and for IWA in all pairs of years. The average r_s values were 0.734 for ARIS and 0.722 for IWA. Household irrigation practices regarding water application and irrigation performance primarily depended on the landowner, whose criteria showed remarkable time stability. The influence of water cost on irrigation decision making was not locally important, probably because the case study presented medium-high income and the cost of irrigation water was relatively low. As a consequence, users did not find an economic incentive to improve water use. This fact contributes to explain the overirrigation observed in the majority of households (Domene and Saurí, 2003).

The correlation coefficient between ARIS and K_L was significant ($P<0.05$) with a r_s of -0.238, indicating an inverse relationship between ARIS and K_L. Landowners specializing in turf produce irrigation schedules more adjusted to water requirements (high K_L is associated with large turf percentage). Trees and shrubs were clearly overirrigated in the study area. Hunt et al. (2001) reported that 38 % of landowners thought that trees and shrubs required as much irrigation water as turf. A significant, negative relationship was found between ARIS and landscape area (r_s = -0.155, $P<0.01$), turf area (r_s = -0.247, $P<0.01$) and percentage of turf area (r_s = -0.225, $P<0.01$). Small landscapes resulted in the highest overirrigation, in agreement with results previously reported by Endter-Wada et al., (2008).

5.4. Irrigation performance in agricultural environments

5.4.1 ET_0, IR_n and IWA

Annual ET_0 values for the different CHE districts are presented in Figure 5.26. Annual ET_0 presented a large variability among the different districts and years of study (840-1,436 mm), with an overall average value of 1,150 mm. Districts located at the Central Ebro Basin area (numbers 3, 4, 12, 14, 16 and 18) generally showed higher ET_0 values than the districts located at the North and South river basin boundaries. The Figure also presents precipitation data for the same years and locations, with an average of 398 mm. Interannual variation in P was much more important than for ET_0, although P had a relatively low weight on the determination of irrigation requirements. The variability in ET_0, precipitation and irrigation water availability within the basin did not permit to analyse seasonal irrigation performance trends responding to dry/wet years. However, it is known that precipitation events reduce ARIS even in well managed irrigation systems (Cavero et al., 2003).

The 1,617 records of IR_n were classified by crop type (Table 5.6). The total area occupied by crops in the database was 10,475 ha, with grain corn and alfalfa occupying the largest areas (6,342 and 1,994 ha, respectively). The average area of plots in each crop ranged between 0.6 ha in apple and 14.4 ha in cherry. The average plot area was 6.5 ha. The overall average value of IR_n in the dataset was 5,693 m^3 ha^{-1}. By crops, the average IR_n ranged (among the CHE districts and years) between 2,683 m^3 ha^{-1} for vineyards RDI and 9,517 m^3 ha^{-1} for rice. Vineyards and winter field crops showed very low IR_n, whereas alfalfa, grain corn and fruit trees with standard irrigation presented very high IR_n. In the crops where RDI was considered (cherry, peach and vineyards), the average IR_n reduction under RDI management was about 18 %.

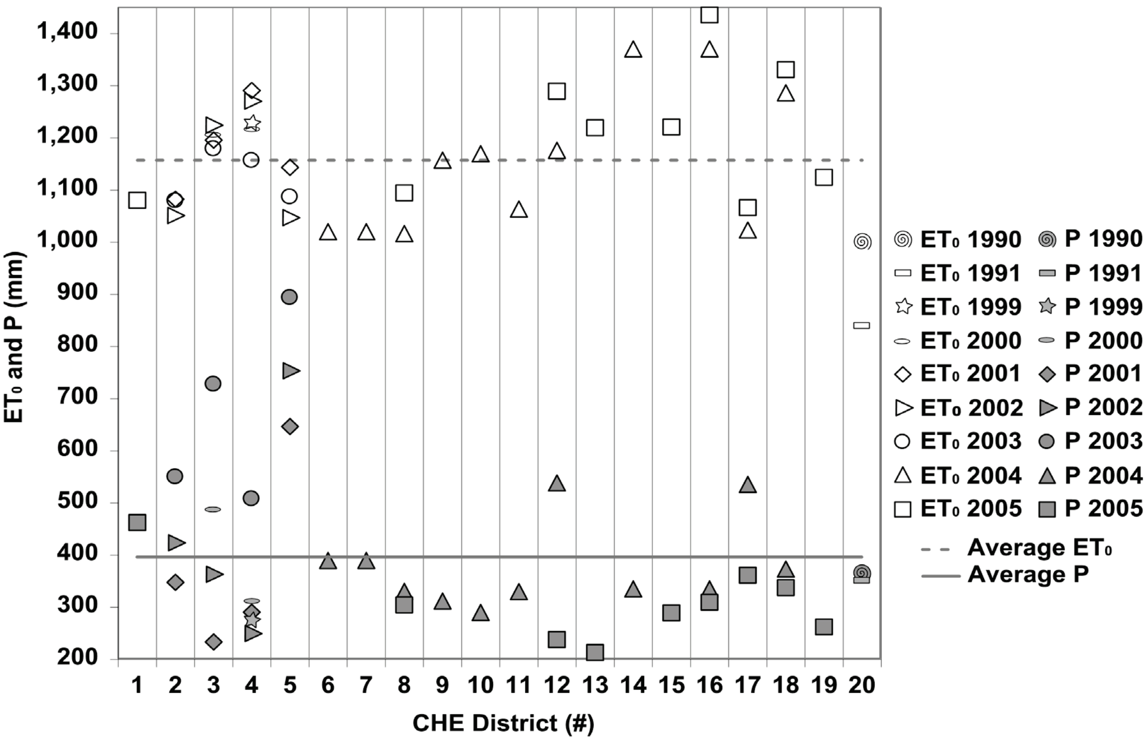


Figure 5.26. Reference evapotranspiration (ET_0, mm) and Precipitation (P) in the different CHE districts for the different data years. The horizontal lines represent average values of ET_0 and P.

Table 5.7 presents values of IWA for each crop stratified by irrigation system. Only 6 of the 18 studied crops used more than one irrigation system, since a clear association between crop and irrigation system could often be observed in the studied area. A few crops (6) had surface irrigated records, being the most important alfalfa, rice and grain corn, with respective percentages of the analysed area under surface irrigation of 38, 28 and 23 %. In sprinkler irrigated plots, grain corn and alfalfa occupied most of the area, with 69 % and 20 % of the land, respectively. In drip irrigated plots, olive trees were present in 33 % of the area, followed by vineyards (22 %).

Table 5.6. Basic statistics corresponding to the net irrigation requirements (IR_n) determined for the different crops.

			Area		IR_n		
Crop type	**Crop**	**Number of records**	**Total (ha)**	**Average (ha)**	**Average ($m^3\ ha^{-1}$)**	**Maximum ($m^3\ ha^{-1}$)**	**Minimum ($m^3\ ha^{-1}$)**
Winter field crops	**Barley**	12	122	10.2	3,335	4,213	2,405
	Peas	21	112	5.3	3,068	3,681	1,844
	Wheat	5	47	9.3	3,992	5,176	2,640
Summer field crops	**Alfalfa**	236	1,994	8.4	6,992	8,935	4,740
	Grain corn	944	6,342	6.7	5,990	7,345	4,389
	Rice	21	147	7.0	9,517	10,223	8,575
	Sunflower	12	50	4.1	5,300	6,355	4,587
Fruit trees	**Apple**	11	6	0.6	5,865	6,663	5,707
	Cherry	8	58	14.4	5,533	6,236	4,657
	Cherry RDI	8	58	14.4	4,599	5,162	3,861
	Peach	22	90	6.0	6,045	7,046	5,095
	Peach RDI	22	90	6.0	4,884	5,734	4,136
	Pear	22	36	1.9	5,899	6,807	5,535
Vegetable crops	**Asparagus**	16	68	4.2	4,860	5,201	4,349
	Onion	34	190	5.6	6,683	7,632	5,942
	Pepper	26	100	3.8	5,528	6,677	4,579
	Potato	10	31	3.1	5,140	5,409	4,737
	Tomato	69	340	4.9	6,063	7,306	5,418
Olive trees	**Olive trees**	49	447	9.1	4,514	5,053	2,048
Vineyards	**Vineyards**	99	296	3.0	3,309	4,591	2,640
	Vineyards RDI	99	296	3.0	2,683	3,790	2,098

Table 5.7. Basic statistics corresponding to the irrigation water application (IWA) determined for the different crops and irrigation systems.

Crop type	Crop	Irrigation system	Number of records	Total area (ha)	IWA Average (m^3 ha^{-1})	IWA SD (m^3 ha^{-1})
Winter field crops	**Barley**	**Solid-set**	9	79	2,602	1,687
		Surface	3	43	1,936	490
		All	**12**	**122**	**2,436**	**1,484**
	Peas	**Solid-set**	21	112	3,526	1,609
	Wheat	**Solid-set**	5	47	2,228	920
Summer field crops	**Alfalfa**	**Solid-set**	211	1,791	8,597	1,793
		Surface	25	202	10,731	1,990
		All	**236**	**1,994**	**8,823**	**1,926**
	Grain corn	**Solid-set**	917	6,218	7,173	1,827
		Surface	27	124	8,077	1,664
		All	**944**	**6,342**	**7,199**	**1,828**
	Rice	**Surface**	21	147	11,404	3,847
	Sunflower	**Solid-set**	9	43	3,460	1,589
		Surface	3	7	3,795	1,229
		All	**12**	**50**	**3,544**	**1,461**
Fruit trees	**Apple**	**Drip**	11	6	3,345	1,425
	Cherry	**Drip**	8	58	6,007	1,609
	Peach	**Solid-set**	3	13	4,492	720
		Drip	19	77	5,865	1,035
		All	**22**	**90**	**5,678**	**1,096**
	Pear	**Drip**	22	36	4,541	1,498

Crop type	Crop	Irrigation system	Number of records	Total area (ha)	IWA Average ($m^3\ ha^{-1}$)	IWA SD ($m^3\ ha^{-1}$)
Vegetable crops	**Asparagus**	**Solid-set**	16	68	2,303	1,221
	Onion	**Solid-set**	34	190	6,972	1,349
	Pepper	**Solid-set**	20	93	5,510	1,193
		Surface	6	7	10,409	1,340
		All	**26**	**100**	**6,641**	**2,423**
	Potato	**Solid-set**	10	31	3,933	1,246
	Tomato	**Solid-set**	69	340	5,394	1,362
Olive trees	**Olive trees**	**Drip**	49	447	2,878	619
Vineyards	**Vineyards**	**Drip**	99	296	1,494	764
(*)		**-**	**1,617**	**10,475**	**6,637**	**1,418**

The overall average IWA was 6,637 $m^3\ ha^{-1}$ (Table 5.7). The crop with the largest average IWA was rice. Other crops with high average IWA were surface irrigated alfalfa and pepper. Sprinkler irrigation records were available in these two crops, and their average IWA were noticeably lower than for surface irrigation (20 and 47 % lower, respectively). The lowest average IWA was found in vineyards (1,494 $m^3\ ha^{-1}$) and surface irrigated barley (1,936 $m^3\ ha^{-1}$). Standard deviations (SD) were relatively high in all cases, with rice (3,847 $m^3\ ha^{-1}$) and pepper (2,423 $m^3\ ha^{-1}$) showing the largest values.

5.4.2 Irrigation performance: basic ARIS statistics

Figure 5.27 presents the average value of ARIS ± SD for the different crops. The line ARIS = 1.00 is presented for reference. The overall average ARIS was 1.08. As previously indicated, this average value indicates slight underirrigation for any irrigation system (even with efficiencies as high as 90 %). This value is much higher than the average value reported by García-Vila et al. (2008) for the Genil-Cabra district (0.60).

The ARIS value was lower than 1.00 in 12 crops. Summer field crops (with the exception of sunflower) had ARIS values higher than 1.00. Fruit trees ARIS presented high variability, with standard management closer to unit values than RDI management. In the case of vineyards, IWA was lower than the IR_n corresponding to RDI management. This seems to correspond to a production strategy related to wine quality, since in the Ebro basin water restrictions are not applied every year, and irrigation water costs in vineyards are not relevant. Olive trees, vineyards and most vegetable crops presented ARIS values clearly indicating underirrigation.

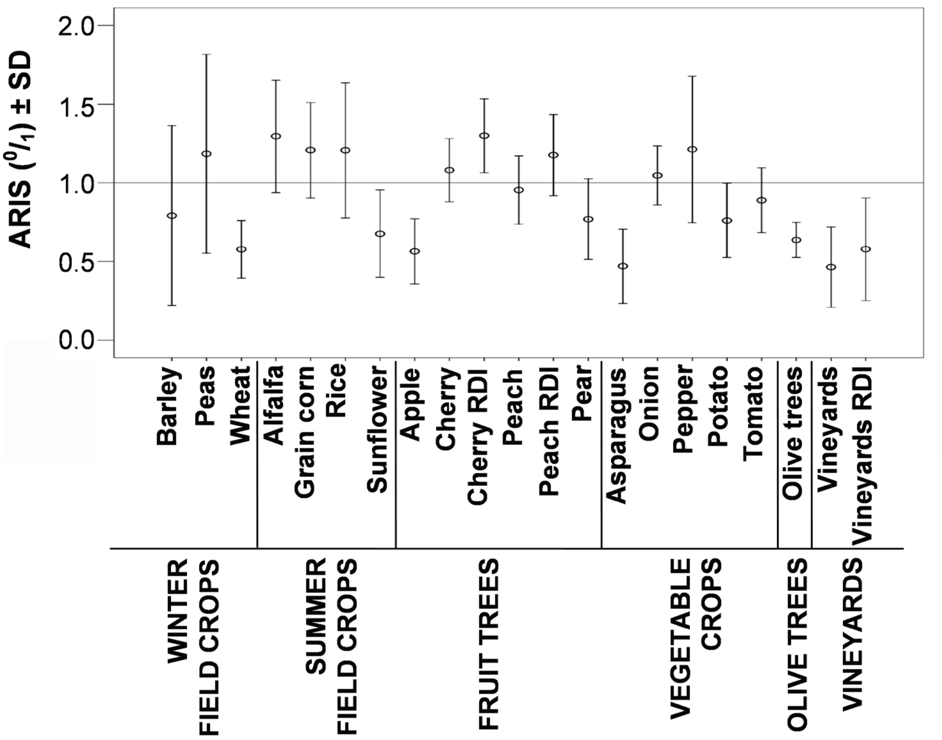


Figure 5.27. Average Annual Relative Irrigation Supply Index (ARIS). Error bars indicate ± standard deviation (SD) in the different crops.

High variability was found in ARIS, affecting all crop groups (Figure 5.27). The ARIS standard deviation (Table 5.8) was 0.29 in average, with the minimum (0.11) corresponding to drip irrigated olive trees and the maximum (0.65) corresponding to solid-set irrigated barley. ARIS variability within each crop was generally high, and could be primarily attributed to variability in irrigation management. Table 5.8 also presents basic ARIS statistics for the combination of crops and irrigation systems. Average ARIS exceeded 1.00 only in 12 of 28 combinations. The lowest average ARIS values were found in drip irrigated vineyards (0.46) and solid-set irrigated asparagus (0.47). The adoption of RDI in fruit trees can be assessed from Table 5.8. Concentrating on drip irrigated cherry and peach, and adopting the 1.11 threshold for ARIS, RDI management results in moderate overirrigation (1.21 for peach and 1.30 for cherry), while standard management results in slight underirrigation (0.99 for peach and 1.08 for cherry). Standard management seems to prevail in these two crops, although RDI seems to be a common practice in the area.

Table 5.8. Basic statistics corresponding to the Annual Relative Irrigation Supply (ARIS) determined for the different crops and irrigation systems.

			ARIS	
Crop type	**Crop**	**Irrigation system**	**Average**	**SD**
Winter field crops	**Barley**	**Solid-set**	0.87	0.65
		Surface	0.55	0.14
		All	**0.79**	**0.57**
	Peas	**Solid-set**	1.18	0.63
	Wheat	**Solid-set**	0.58	0.18
Summer field crops	**Alfalfa**	**Solid-set**	1.25	0.31
		Surface	1.64	0.52
		All	**1.30**	**0.36**
	Grain corn	**Solid-set**	1.20	0.30
		Surface	1.40	0.38
		All	**1.21**	**0.30**
	Rice	**Surface**	1.21	0.43
	Sunflower	**Solid-set**	0.63	0.28
		Surface	0.81	0.26
		All	**0.68**	**0.28**

			ARIS	
Crop type	**Crop**	**Irrigation system**	**Average**	**SD**
Fruit trees	**Apple**	**Drip**	0.56	0.21
	Cherry	**Drip**	1.08	0.20
	Cherry RDI	**Drip**	1.30	0.24
	Peach	**Solid-set**	0.74	0.19
		Drip	0.99	0.20
		All	**0.95**	**0.22**
	Peach RDI	**Solid-set**	0.97	0.27
		Drip	1.21	0.25
		All	**1.18**	**0.26**
	Pear	**Drip**	0.77	0.26
Vegetable crops	**Asparagus**	**Solid-set**	0.47	0.24
	Onion	**Solid-set**	1.05	0.19
	Pepper	**Solid-set**	1.00	0.22
		Surface	1.93	0.32
		All	**1.21**	**0.47**
	Potato	**Solid-set**	0.76	0.24
	Tomato	**Solid-set**	0.89	0.21
Olive trees	**Olive trees**	**Drip**	0.64	0.11
Vineyards	**Vineyards**	**Drip**	0.46	0.26
	Vineyards RDI	**Drip**	0.58	0.33

Considering previous work in the area, our results for surface irrigation show lower ARIS than reported by Faci et al. (2000) for 1994 in corn and sunflower. Recent improvements in local surface irrigation management can explain these differences, as evidenced by Lecina et al. (2005). In solid-sets, however, results from the literature (Cavero et al., 2003; Dechmi et al., 2003a and Zapata et al., 2009) fit in the reported distribution of ARIS values. Improved control of water application and relevant energy costs contribute to the fact that ARIS values in the area are lower for solid-set irrigation than for surface irrigation.

ARIS in the Ebro basin and in the Genil-Cabra area can be compared for the four crops in present in both studies (Lorite et al., 2004). Winter cereals ARIS in Genil-Cabra was 0.39 compared to 0.79 for barley and 0.58 for wheat in the Ebro basin; grain corn was 0.73 compared to 1.21 in the Ebro basin; sunflower was 0.28 compared to 0.68 in the Ebro basin; and olive trees was 0.37 compared to 0.64 in the Ebro basin. The lower ARIS values reflect more water scarcity at the Genil-Cabra district. Larger ARIS variability could be expected at the Ebro basin than at the Genil-Cabra district, owing to the differences in geographic extension, climate, soils and irrigation technologies. However, clear differences in ARIS variability between both areas could not be established, with crop ARIS SD ranging between 0.18 and 0.31 at the Genil-Cabra district and between 0.11 and 0.57 at the Ebro basin.

Figure 5.28 presents three scatter plots where IR_n and IWA are compared for a) all data set records; b) crop types; and c) irrigation systems. Considering all data set records, most of the points showing low IR_n are located below the diagonal line, while points with high IR_n are generally located above it (Fig. 5.28a). All crop types excepting summer field crops are located below the 1:1 line, with olive trees and vineyards clearly deviating from it on the underirrigation side (Fig. 5.28b). Clear differences between the three irrigation systems were found (Fig. 5.28c). Surface irrigated plots presented IWA clearly higher than IR_n (ARIS = 1.41). Solid-set and drip systems were located closer to the 1:1 line. Solid-set irrigated plots showed slightly higher IWA than IR_n (ARIS = 1.16), and drip irrigated plots showed clear underirrigation (ARIS = 0.65).

The relationship between irrigation systems and crops is further explored in Figure 5.29. Four surface irrigated crops (rice, alfalfa, pepper and grain corn) showed higher IWA than IR_n (Fig. 5.29a). For solid-set sprinkler irrigation, only summer field crops and onion showed IWA higher than IR_n (Fig. 5.29b). For drip irrigation, only peach RDI and cherry (both standard and RDI) presented IWA higher than IR_n (Fig. 5.29c), and in all cases near of the 1:1 line.

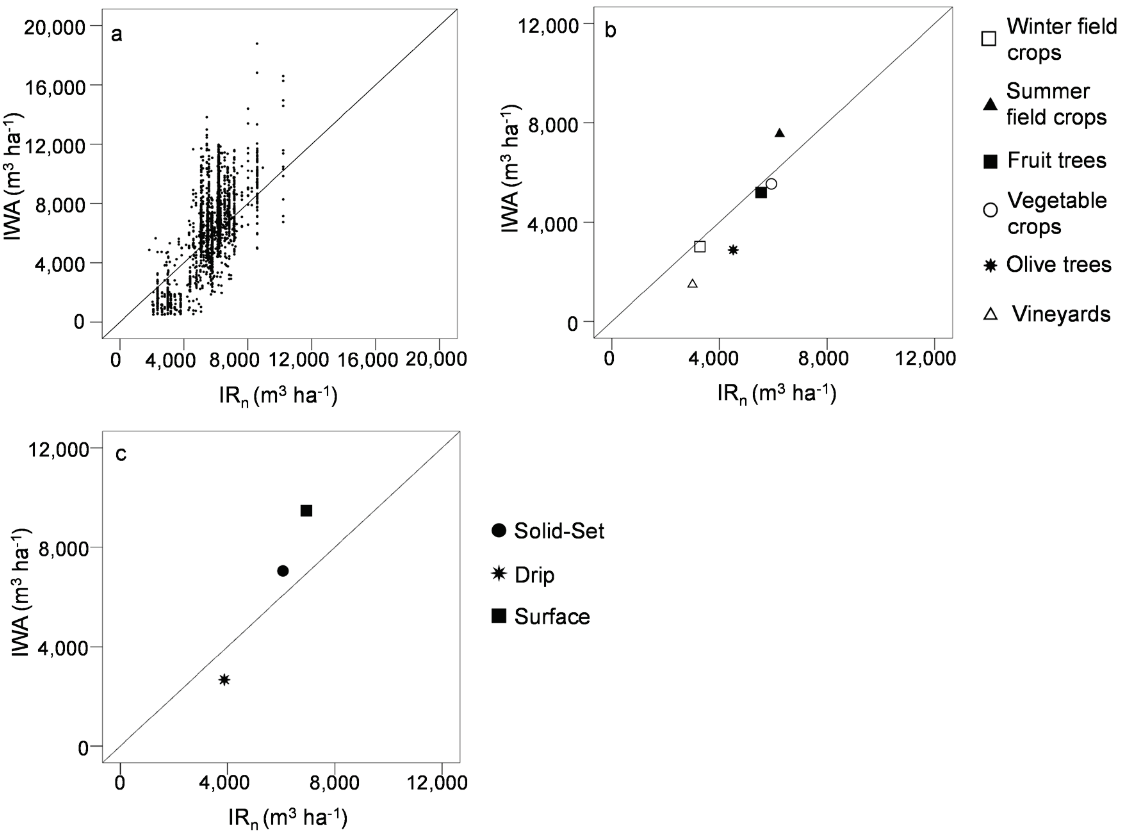


Figure 5.28. Comparison of net Irrigation Requirements (IR_n) and Irrigation Water Applied (IWA) considering the different: a) all data, b) crop type, and c) irrigation systems.

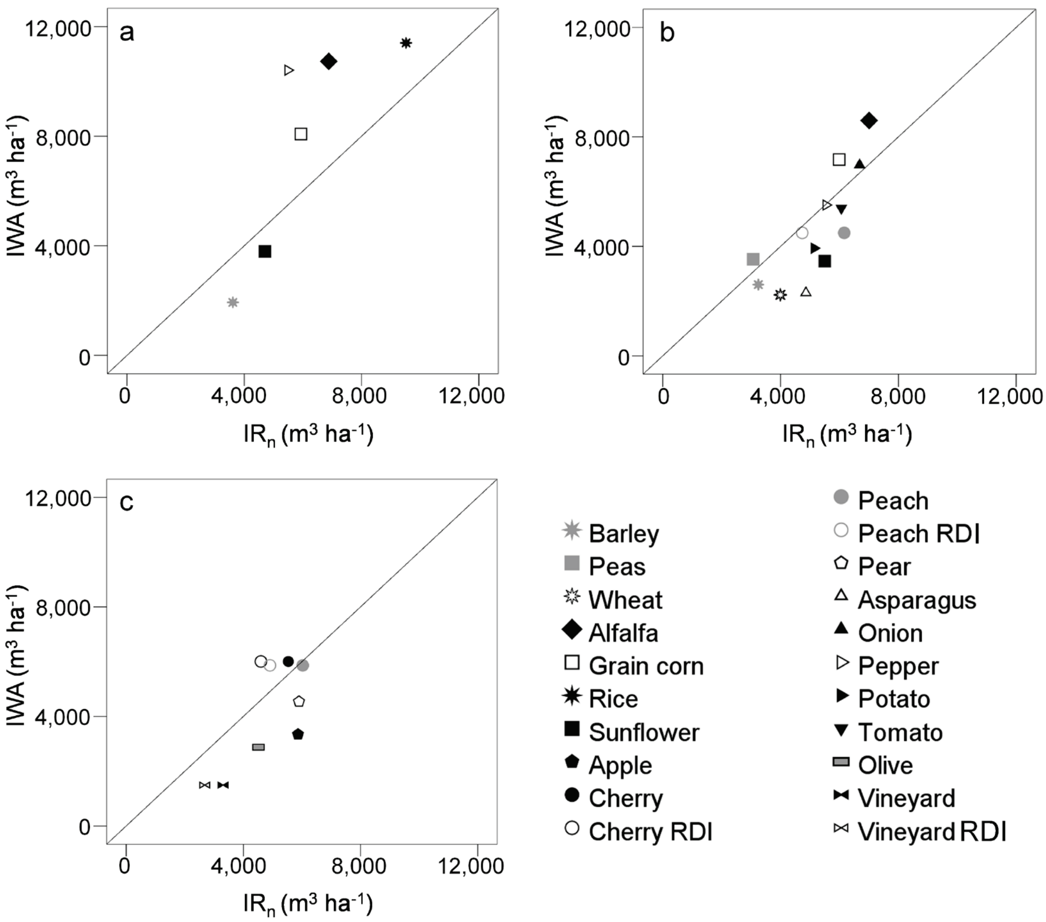


Figure 5.29. Comparison of net Irrigation Requirements (IR_n) and Irrigation Water Applied (IWA) in the different crops, considering the irrigation systems: a) surface, b) solid-set sprinkler, and c) drip irrigation.

5.4.3 Irrigation performance: classification of ARIS results

A cluster classification analysis was performed for each combination of crop – irrigation system using IR_n and IWA as independent variables (Figure 5.30). Four main groups (A, B, C and D) were obtained, two of which (B and C) were divided in two subgroups (1 and 2). Figure 5.31 presents a scatter plot of IR_n and IWA for the crop – irrigation system combinations belonging to each subgroup resulting from the cluster analysis. Group A presented very high values of IWA and IR_n. Group B was characterized by medium-high IR_n, and was divided in two subgroups: B1 with very high IWA and B2 with high IWA. Group C was characterized by medium-high IR_n and medium (C1) or low (C2) IWA. Group D included combinations of crop-irrigation system showing low IR_n and very low IWA.

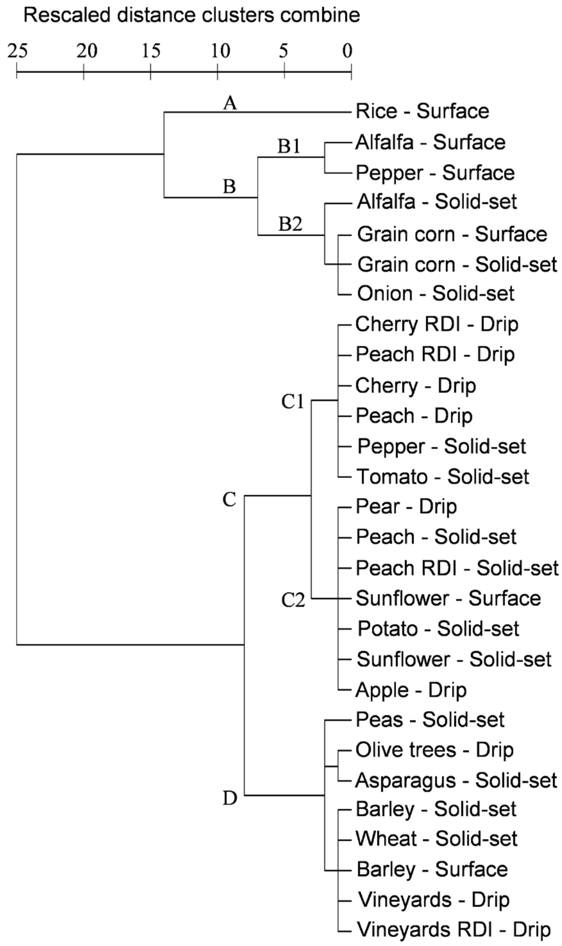


Figure 5.30. Cluster classification of the compound variable crop x irrigation system obtained by the analysis of net Irrigation Requirements (IR_n) and Irrigation Water Applied (IWA).

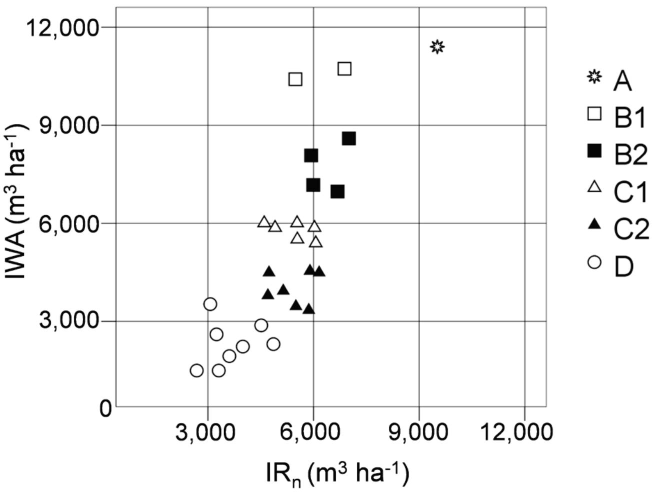


Figure 5.31. Comparison of net Irrigation Requirements (IR_n) and Irrigation Water Applied (IWA) considering the different groups defined by the cluster analysis.

5.4.4 Irrigation water productivity

Irrigation water productivity in the Aragón region was determined for ten crop – irrigation system combinations (Table 5.9). The variability in productivity between crops and irrigation systems was large, and increased from WP_T to WP_{Eg} and to WP_{En}. The ratios of maximum to minimum productivity were 14, 16 and 24, respectively. Transition from WP_T to WP_{En} increased the observed differences between crops and irrigation systems. In the case of barley, alfalfa, grain corn and sunflower, solid-set irrigated crops had higher water productivities than surface irrigated crops, due to the fact that irrigation depth was lower and yield was higher in sprinkler irrigation than in surface irrigation.

Table 5.9. Technical Water productivity (WP_T), gross economic Water Productivity (WP_{Eg}) and net economic Water Productivity (WP_{En}) for selected crops and irrigation systems.

			Water Productivity		
Crop type	**Crop**	**Irrigation system**	**WP_T (Kg m^{-3})**	**WP_{Eg} (€ m^{-3})**	**WP_{En} (€ m^{-3})**
Winter field crops	**Barley**	**Solid-set**	2.5	0.26	0.20
		Surface	2.3	0.28	0.19
	Wheat	**Solid-set**	1.6	0.19	0.043
Summer field crops	**Alfalfa**	**Solid-set**	1.8	0.11	0.083
		Surface	1.1	0.077	0.052
	Grain corn	**Solid-set**	1.6	0.16	0.13
		Surface	1.2	0.13	0.10
	Rice	**Surface**	0.45	0.081	0.059
	Sunflower	**Solid-set**	0.68	0.11	0.068
		Surface	0.53	0.089	0.045
Fruit trees	**Apple**	**Drip**	6.4	1.2	1.0
	Peach	**Drip**	4.1	0.91	0.74
	Pear	**Drip**	4.2	1.1	0.91
Olive trees	**Olive trees**	**Drip**	1.1	0.52	0.42

WP_{Eg} and WP_{En} showed similar trends as WP_T regarding crops and irrigation systems, although costs were higher for solid-set sprinkler systems than for surface irrigation systems. Comparing the two most frequent crops in the Ebro basin, grain corn showed higher economic productivities than alfalfa. Rodrigues and Pereira (2009) presented results of water productivity for three crops in a sprinkler irrigated area near Évora (south of Portugal). Different deficit irrigation scenarios, locations, dry/wet years and potential application efficiencies were considered. Comparisons with the present study could be established in terms of WP_T. Technical productivity was higher in Portugal, with ranges of 1.11-2.75 kg m^{-3} for corn, 0.61-2.46 kg m^{-3} for sunflower, and 1.48-15.44 kg m^{-3} for wheat. The comparatively low crop water requirements at Évora and the use of deficit irrigation contributed to these high productivity figures. When comparisons in WP_{Eg} were established between the Genil-Cabra district (period 1997 - 2000) (Lorite et al., 2004) and the Aragón region (period 2001 - 2005), irrigation water productivity was higher in the Genil-Cabra district for the four common crops: sprinkler irrigated winter cereals (0.91 € m^{-3} vs. 0.26 € m^{-3} for barley and 0.19 € m^{-3} for wheat), sprinkler irrigated grain corn (0.28 € m^{-3} vs 0.16 € m^{-3}), sprinkler irrigated sunflower (0.56 € m^{-3} vs. 0.11 € m^{-3}), and drip irrigated olive trees (2.34 € m^{-3} vs. 0.52 € m^{-3}). These differences were heavily influenced by irrigation water application: deficit irrigation in Genil-Cabra increased economic productivity. Although the Ebro basin and the Genil-Cabra district are similar in many aspects, differences in the agricultural and economic context, and in the analysed period, make comparisons difficult.

6. CONCLUSIONES

6. CONCLUSIONES

Caracterización de las gotas emitidas por un aspersor agrícola

1. La técnica propuesta permite estimar diámetro de gotas, velocidad y ángulo de caída a través de medidas directas, lo cual garantiza la calidad en la caracterización de las gotas presentes en las fotografías. Las medidas de velocidad y diámetro de gotas han sido validadas, con errores medios de -0,45 y 0,31 % respectivamente.
2. La caracterización de gotas mediante esta técnica no requiere equipamiento específico, pero es un método muy laborioso que requiere una elevada inversión de tiempo. Esta característica, no obstante, es común a otras técnicas de medida directa de gotas.
3. En el ensayo experimental, los resultados confirman las diferencias de diámetro, velocidad y ángulo de caída a diferentes distancias del aspersor. El método permite caracterizar de forma independiente las gotas emitidas por el brazo del aspersor a distancias de 6,0 y 7,5 m del aspersor. Las diferencias entre las gotas desviadas por la pala y las emitidas directamente por la boquilla del aspersor son relevantes.
4. Con los resultados obtenidos, se confirma la necesidad de reformular la teoría balística en los modelos de simulación del riego por aspersión. Esta teoría no explica, por ejemplo, la aparición de gotas de pequeño tamaño (<1 mm de diámetro) cerca del aspersor.
5. La distribución del diámetro de gotas y la velocidad de caída de las mismas presentan tendencias muy similares, mientras que el ángulo muestra una elevada variabilidad a varias distancias (particularmente para gotas finas), posiblemente debido a turbulencias ambientales.
6. La metodología propuesta tiene una clara aplicación en la aportación de datos a los simuladores de riego por aspersión para la mejora de las hipótesis incluidas en los modelos balísticos.

Programación de riego en redes presurizadas: el factor humano

7. En la comunidad de regantes estudiada, no se encontró relación entre la meteorología y el manejo del agua de riego en los hidrantes individuales. Esto parece ser debido a que el agua se solicita por los agricultores con dos días de antelación. Sin embargo, el número total de hidrantes funcionando en cada momento está relacionado en muchos casos con la precipitación, velocidad de viento (r_s = -0,285), humedad relativa (r_s = 0,418) y temperatura del aire (r_s = -0,469).
8. La hora de comienzo del riego presenta dos periodos de mayor frecuencia situados en torno a las 8:00 y las 20:00, definiendo claramente el tipo de riego diurno y nocturno. Los periodos en los que menos frecuente resulta el inicio del riego son las horas centrales tanto del día como de la noche.
9. Los patrones de aplicación del agua de riego se clasificaron en función del promedio de riegos semanales, la desviación estándar del promedio de riegos semanales y la moda del rango horario de la hora inicio del riego. Como resultado de la clasificación se obtuvieron un total de 10 grupos de patrones de aplicación del agua de riego. Las variables que explican dicha clasificación son el regante (56,4 %), el sistema de riego (32,9 %) y el cultivo (10,7 %). Dentro del factor humano se integran tanto el nivel de conocimientos como la experiencia.
10. En un 22 % de las combinaciones regante-sistema de riego se aprecia una cierta evolución temporal en los patrones de riego. Sin embargo, en un 39 % de los casos los cambios de patrón de riego tienen una apariencia aleatoria.
11. Un 45 % de los regantes utilizan el mismo patrón de riego independientemente del cultivo regado en un 50 % o más de sus combinaciones hidrante-año. Sólo en un 14 % de los regantes se aprecia una especialización resultante en aplicar distintos patrones de riego para distintos cultivos.
12. Los resultados demuestran que los regantes de esta comunidad no valoran la importancia o no tienen capacidad para aplicar patrones de riego más consistentes con las condiciones medioambientales que rodean a los cultivos.

Adecuación del riego en entornos urbanos

13. El promedio de agua utilizada por vivienda (uso doméstico y riego de jardín) fue de 0,80 m^3 vivienda^{-1} día^{-1}. El volumen de agua de riego de los jardines supuso un 46 % del volumen total de agua usada por vivienda (valores entre 38 % en marzo-abril y 69 % en julio-agosto).
14. El máximo volumen de consumo de agua doméstica se registró durante el periodo bimensual de mayo-junio, con un promedio de 27,3 m^3, siendo el volumen mínimo registrado en los meses de julio-agosto (21,4 m^3 de promedio).
15. La zona estudiada presentaba una red de abastecimiento diferente para el agua de riego y para el agua doméstica (potable). Este hecho permitió estimar el error cometido en las habituales estimaciones de consumo de agua de riego en lugares con una única red de abastecimiento. En estas zonas, el agua de riego se calcula como la diferencia entre el agua total utilizada y el promedio del agua consumida en los meses invernales. Con esta estimación se puede subestimar el valor bimensual de agua destinada al riego en un 23 %. En todo caso, estas diferencias se producirían en zonas con hábitos vacacionales similares a los españoles (vacaciones muy concentradas en los meses de julio y agosto). En cualquier caso, para un análisis preciso del uso del agua de riego en jardines privados, resulta necesaria la instalación de contadores de agua específicos.
16. El promedio de la temperatura diaria del aire determina en gran medida el volumen de agua de riego utilizado (r_s = 0,958). Los picos de precipitación registrados durante el periodo estudiado no tuvieron influencia en el volumen de agua utilizada para el riego.
17. El exceso de riego resultó habitual en los tres años estudiados, con un promedio de agua aplicada mucho mayor a las necesidades hídricas netas (1359 y 555 mm respectivamente). Aunque en los periodos marzo-abril y septiembre-octubre las necesidades hídricas netas son similares, el volumen de agua aplicada es mucho mayor en septiembre-octubre que en marzo-abril. Estos datos confirman la hipótesis inicial de exceso de riego de los jardines al final de la campaña de riego.

18. Se realizó una clasificación con conglomerados jerárquicos analizando las diferencias entre el volumen de agua aplicada y las necesidades hídricas netas. Se identificaron cuatro grupos con diferencias sustanciales entre ellos. El subgrupo A1, el cual contiene el 34 % de las viviendas, es el único que presenta una adecuada aplicación del agua de riego. En cuanto a los demás grupos, tres de ellos presentan intenso sobrerriego, mientras que el grupo B (al que pertenecen el 6 % de las viviendas) se caracteriza por aplicar un volumen de agua inferior las necesidades hídricas netas.
19. La evaluación de la calidad del riego mostró un exceso de riego generalizado, con promedio de ARIS (*Annual Relative Irrigation Supply*, índice anual de suministro de riego) de 2,52. La combinación en la zona estudiada de precios del agua de riego relativamente bajos y elevados ingresos, hace que los usuarios tiendan a aplicar más agua de la necesaria.
20. La optimización del riego en los jardines privados resulta más compleja que la optimización del riego en la agricultura, debido a las diferencias en la percepción del coste del agua de riego y los beneficios.

Adecuación del riego en entornos agrícolas

21. El cultivo con un valor promedio de agua aplicada más bajo es la viña debido a que en muchos casos la cantidad de agua de riego proporcionada al cultivo viene marcado por las preferencias del mercado. El cultivo con un promedio más elevado de agua aplicada es el arroz.
22. El promedio general de los valores de ARIS es 1,08, sugiriendo un ligero déficit hídrico. Los cultivos extensivos de verano (excepto el girasol) y frutales bajo riego deficitario controlado (RDC) presentan los mayores valores de ARIS.
23. Para un determinado cultivo, el ARIS resulta generalmente menor bajo riego con cobertura total que en riego por superficie. El promedio de las diferencias es 0,20 en maíz (14 % menor) y 0,39 en alfalfa (24 % menor).
24. En el análisis de cluster se identificaron cuatro grupos significativamente diferentes, resultando necesaria para la correcta clasificación la asociación entre cultivo y sistema de riego. De hecho, las diferencias comentadas entre sistemas de riego son muy relevantes en la explicación de las diferencias entre cultivos.
25. En general, la productividad del agua de riego es mayor bajo riego en cobertura total que bajo riego por superficie. Las diferencias entre las distintas asociaciones de sistema de riego y cultivo para los tres valores de productividad estudiados son moderadas.
26. El ARIS resultó ser un indicador adecuado para estudiar la calidad del riego en parcela, permitiendo su aplicación en grandes superficies con un esfuerzo moderado. Sin embargo, es un indicador insuficiente para juzgar la adecuación del riego a nivel de cuenca.

7. REFERENCES

7. REFERENCES

Ahmad M.D., Masih I. and Turral H., 2004. Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab, Pakistan. Journal of Applied Irrigation Science, Vol. 39. Nº 1/2004, pp. 43 – 63.

Allen R.G., Pereira L.S., Raes D. and Smith M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Aquacraft-Inc., 2003. Analysis of Operation of WeatherTRAK Controller in Field Conditions During 2002. Report on Performance of ET Based Irrigation Controller. Retrieved from: http://www.aquacraft.com/Download_Reports/WeatherTRAK_2001_Study_Report.pdf

Ayuntamiento de Zaragoza, 1999. Plan General de Ordenación Urbana de Zaragoza. Memoria Informativa. Zaragoza, Spain. Retrieved from: http://www.zaragoza.es/ciudad/urbanismo/planeamiento/pgouz/memoria.htm.

Ayuntamiento de Zaragoza, 2004. Ordenanza Fiscal nº 24.25. Tasa por la prestación de servicios de abastecimiento de agua potable y saneamiento de aguas residuales. Ordenanzas municipales. Zaragoza, Spain. Retrieved from: http://www.zaragoza.es/contenidos/normas/ord_fiscales/2004/ordenanza_24_25.pdf.

Bauman, D.D., Boland J.J. and Hanemann W.M., 1998. Urban Water Demand Management and Planning. (pp. 77-94). McGraw- Hill, New York, USA.

Bedaiwy M.N.A., 2008. Mechanical and hydraulic resistance relations in crust-topped soils. Catena 72(2): 270-281.

Boland, J.J., Dziegielewski, B., Baumann, D.D. and Opitz, E.M., 1984. Influence of price and rate structures on municipal and industrial water use. U.S. Army Engineer Institute for Water Resources., Fort Belvoir, Va.

Brouwer, C. and Heibloem, M., 1986. Irrigation Water Management: Irrigation Water Needs. Training manual number 3. FAO, Rome, Italy.

Brown, P.D., Cochrane, T. and Krom, T.D., 2010. Optimal on-farm irrigation scheduling with a seasonal water limit using simulated annealing. Agricultural Water Management, 97(6), 892-900.

Brown, P.W., Mancino, C.F., Young, M.H., Thompson, T.L., Wierenga, P.J. and Kopec, D.M., 2001. Penman Monteith Crop Coefficients for Use with Desert Turf Systems. Crop Science, 41(1992), 1197-1206.

Buendia-Espinoza J.C., Palacios-Velez E., Chavez-Morales J. and Rojas-Martinez B., 2004. Impact of pressurized irrigation systems performance on productivity of eight crops, in Guanajuato, Mexico. Agrociencia, 38 (5), 477-486.

Burguete, J., Playán, E., Montero, J. and Zapata, N., 2007. Improving drop size and velocity estimates of an optical disdrometer: Implications for sprinkler irrigation simulation. Transactions of the ASABE, 50(6), 2103-2116.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R., Hardy, L.A., Howell, T.A. and Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. Journal of Irrigation and Drainage. Div., ASCE, 123(6), 423-442.

Cancela, J.J., Cuesta, T.S., Neira, X.X. and Pereira, L.S., 2006. Modelling for Improved Irrigation Water Management in a Temperate Region of Northern Spain. Biosystems Engineering, 94(1), 151-163.

Carrión P., Tarjuelo J.M. and Montero J., 2001. SIRIAS: a simulation model for sprinkler irrigation: I. Description of the model. Irrigation Science, 2001(20), 73-84.

Cavero, J., Beltrán, A. and Aragüés, R., 2003. Nitrate exported in the drainage waters of two sprinkler irrigated watersheds. Journal of Environmental Quality, 32(2003), 916-926.

Chopart, J. L., Mezino, M., Aure, F., Le Mézo, L., Mété, M. and Vauclin, M., 2007. OSIRI: A simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments. Agricultural Water Management, 87, 128-138.

Clemmens, A.J. Arranged delivery schedules., 1987. In: Planning, operation, rehabilitation and automation of irrigation water delivery systems. D. D. Zimbelman (Ed.), Proceedings of a Symposium, July 28-30, 1987, Portland, OR, USA. Irrigation and Drainage Division, American Society of Civil Engineers. pp. 57-80.

Clemmens, A.J. and Dedrick, R., 1992. Identifying factors that influence farm water use. Technical papers, volume II. Conferencia regional panamericana. Mazatlán, Sinaloa, México.

Clemmens, A.J. and Dedrick, A.R., 1994. Irrigation Techniques and Evaluations. Adv. Series in Agricultural Sciences. 22, 63-103.

Confederación Hidrográfica del Ebro., 2008. Información básica de la cuenca del Ebro. Ministerio de Medio Ambiente y Medio Rural y Marino, Gobierno de España. Retrieved from: http://www.chebro.es.

Contreras, F., González, A., López, J. and Calvo, A., 2006. Estimación de necesidades hídricas para especies de jardín en la región de Murcia: Adaptación de WUCOLS y utilización del sistema de información agraria de Murcia. III Jornadas Ibéricas de Horticultura Ornamental. (pp. 1-10). Almería.

Cortignani, R. and Severini, S., 2009. Modeling farm-level adoption of deficit irrigation using Positive Mathematical Programming. Agricultural Water Management, 96, 1785-1791.

Costello, L. and Jones, K.S., 1994. WUCOLS. Water Use Classification of Landscape Species: A Guide to the Water Needs of Landscape Plants. University of California, Cooperative Extension. Sacramento, California, USA. Retrieved from: http://ucce.ucdavis.edu/files/filelibrary/1726/15359.pdf

Costello, L.R., Matheny, N.P. and Clark, J.R., 2000. A Guide to Estimating Irrigation Water Needs of Landscape Plantings in California. The Landscape Coefficient Method and WUCOLS III. Water Resources. Sacramento, Califonia: University of California Cooperative Extension. Retrieved from: http://www.water.ca.gov/wateruseefficiency/docs/wucols00.pdf

Cruvinel, P.E., Minatel, E.R., Mucheroni, M.L., Vieira, S.R. and Crestana, S., 1996. An Automatic Method Based on Image Processing for Measurements of Drop Size Distribution from Agricultural Sprinklers. Anais do IX SIBIGRAPI, 39-46.

Cruvinel, P.E., Vieira, S.R., Crestana, S., Minatel, E.R., Mucheroni, M.L. and Neto, A.T., 1999. Image processing in automated measurements of raindrop size and distribution. Computers and Electronics in Agriculture, 23(3), 205-217.

Cuenca R.H., 1989. Irrigation system design: an engineering approach, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Davis, S.L., Dukes, M.D. and Miller, G.L., 2009. Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in Southwest Florida. Agricultural Water Management, 96(12), 1828-1836.

De Juan, J.A. and Martín De Santa Olalla, F., 1993. Las funciones de producción versus agua. Eds. MundiPrensa. Madrid.

De Lima, J.L.M.P. and Torf, P.J.J.F., 1994. Effects of wind on simulated rainfall and overland flow under single full-cone nozzle sprays. Proceedings of the Second European Conference on Advances in Water Resources Technology and Management. pp. 443–450, In: Trakiris, G. and Santos, M.A., Editors,, Balkema, Lisbon, Portugal.

De Lima, J.L.M.P., Torfs, P.J.J.F. and Singh V.P., 2002. A mathematical model for evaluating the effect of wind on downward-spraying rainfall simulators. Catena, 46(4), 221-241.

Dechmi, F., Playán, E., Faci, J. M. and Tejero, M., 2003a. Analysis of an irrigation district in northeastern Spain I. Characterisation and water use assessment. Agricultural Water Management, 61(2), 75-92.

Dechmi, F., Playán, E., Faci, J.M., Tejero, M. and Bercero, A., 2003b. Analysis of an irrigation district in northeastern Spain II. Irrigation evaluation, simulation and scheduling. Agricultural Water Management, 61, 93-109.

Department of WaterResources. Office of water use efficeny., 2011. California irrigation management information system. Retrieved from: http://wwwcimis.water.ca.gov/cimis/welcome.jsp.

Devitt, D.A., Carstensen, K. and Morris, R.L., 2008. Residential Water Savings Associated with Satellite-Based ET Irrigation Controllers. Journal of Irrigation and Drainage. E-ASCE, 134(1), 74-82.

Domene, E. and Saurí, D., 2003. Modelos urbanos y consumo de agua. El riego de jardines privados en la región metropolitana de Barcelona. Investigaciones Geográficas, 32, 5-17.

Domene, E. and Saurí, D., 2006. Urbanization and Water Consumption: Influencing Factors in the Metropolitan Region of Barcelona. Urban Studies, 43(9), 1605-1623.

Doorenbos, J. and Pruitt, W. H., 1992. Crop water requirements. (Vol. 24). Food and Agriculture Organization of the United Nations.

Edling, R.J., 1985. Kinetic energy, evaporation and wind drift of droplets from low pressure irrigation nozzles. Transactions of the American Society of Agricultural Engineers 28(5): 1543-1550.

Eigel, J. D. and Moore, I. D., 1983. A simplified technique for measuring raindrop size and distribution. Transactions of American Society of Agricultural Engineers, 26(4), 1079-1084.

Endter-Wada, J., Kurtzman, J., Keenan, S. P., Kjelgren, R. K. and Neale, C. M. U., 2008. Situational waste in landscape watering: residential and business water use in an urban Utah community. Journal Of The American Water Resources Association, 44(4), 902-920.

European Parliament, 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. European Parliament, Council.

Faci, J.M., Bensaci, A., Slatni, A. and Playán, E., 2000. A case study for irrigation modernisation: I. Characterisation of the district and analysis of water delivery records. Agricultural Water Management, 42 (3) (2000), 313-334.

FAO, 1974. FAO/Unesco Soil Map of the World 1:5.000.000. FAO-Unesco, Paris.

Faysse, N., 2003. Allocating irrigation water : the impact of strategic interactions on the efficiency of rules. European Review of Agricultural Economics, 30(3), 305-332.

Fernández M.D., González A.M., Carreño J., Pérez C. and Bonachela S., 2007. Analysis of on-farm irrigation performance in Mediterranean greenhouses. Agricultural Water Management, 89 (3), 251-260.

Fukui, Y., Nakanishi, K. and Okamura, S., 1980. Computer evaluation of sprinkler irrigation uniformity. Irrigation Science, 2, 23-32.

García-Vila M., Lorite I.J., Soriano M.A. and Fereres E., 2008. Management trends and responses to water scarcity in an irrigation scheme of Southern Spain. Agricultural Water Management, 95 (4), 458-468.

Generalitat de Catalunya, 2002. Riego. Dades metereològiques. RuralCat. Departamento de Agricultura, Alimentación y Acción Rural de la Generalitat de Catalunya. Retrieved from: http://www.ruralcat.net/ruralcatApp/agrometeo/html/agrometeo.htm.

Girona J., 1996. Coeficients de cultiu. Centre R+D de Lleida. Institut de Recerca i Tecnologia Agroalimentàries, Lleida, España.

Government of Aragón, 2008. Servicio de Información Territorial de Aragón (SITAR). Retrieved from: http://sitar.aragon.es.

Government of Aragón., 2011. Necesidades hídricas de los cultivos (Irrigation requirements of crops). Retrieved from: http://servicios.aragon.es/oresa/necesidadHidrica.inicioPublico.do?sm=5.

Government of Navarra, 2003. Meteorología y Climatología de Navarra. Datos de las Estaciones. Departamentos de Desarrollo Rural e Industria, Gobierno de Navarra. Retrieved from: http://meteo.navarra.es/estaciones/mapadeestaciones.cfm

Haley, M.B., Dukes, M.D. and Miller, G.L., 2007. Residential Irrigation Water Use in Central Florida. Journal of Irrigation and Drainage Engineering, 133(5), 427-434.

Han, J. and Kamber, M., 2006. Data Mining: Concepts and Techniques. (Elsevier, Eds.). Morgan Kaufmann Publishers.

Hauser, D., Amayenc, P., Nutten, B. and Waldteufel, P., 1984. A new optical instrument for simultaneous measurement of raindrop diameter and fall speed distributions. Journal of Atmospheric and Oceanic Technology, 1(3), 256-269.

Hirsch, F., 1976. Social limits to growth. Harvard University Press. Cambridge, Massachusetts, USA.

Hunt, T., Lessick, D., Berg, J., Wiedmann, J., Ash, T., Pagano, D., Maiam, M. and Bamezai, A., 2001. Residential Weather-Based Irrigation Scheduling: Evidence from the Irvine “ET Controller” Study. Retrieved from: http://www.irrigation.org/swat/images/irvine.pdf.

Hurd, B.H., St. Hilaire, R. and White, J.M., 2006. Residential landscapes, homeowner attitudes, and water-wise choices in New Mexico. Hortscience, 16(2), 241-246.

Igbadun, H.E., Mahoo, H.F., Tarimo, A.K.P.R. and Salim, B.A., 2006. Crop water productivity of an irrigated maize crop in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania. Agricultural Water Management, 85 (1-2), 141-150.

Jalota, S.K., Sood, A., Vitale, J.D. and Srinivasan, R., 2007. Simulated crop yields response to irrigation water and economic analysis: Increasing irrigated water use efficiency in the Indian Punjab. Agronomy Journal, 99 (4), 1073-1084.

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrigation Science, 25 (3), 233-245.

Jones, D. M. A., 1956. Rainfall drop-size distribution and radar reflectivity. Illinois state water survey. Meteorology Laboratory, research report nº 6.

Joss, J. and Waldvogel, A., 1967. Ein Spectrograph für Niederschlagstropfen mit automatisher Auswertung (A spectrograph for the automatic analysis of raindrops). Pure and Applied Geophysics., 68, 240-246.

Kahlown, M.A., Raoof, A., Zubair, M. and Kemper, W.D., 2007. Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. Agricultural Water Management, 87 (3), 292-298.

Karami, E., 2006. Appropriateness of farmers’ adoption of irrigation methods: The application of the AHP model. Agricultural Systems, 87, 101-119.

Keller, J. and Bliesner, R.D., 1990. Sprinkle and trickle irrigation. New York, NY, Van Nostrand Reinhold.

Khadra, R., and Lamaddalena, N., 2010. Development of a Decision Support System for Irrigation Systems Analysis. Water Resources Management, 24, 3279-3297.

Kincaid, D.C., 1996. Spraydrop kinetic energy from irrigation sprinklers. Transactions of the American Society of Agricultural Engineers 39(3): 847-853.

Kincaid, D.C., Solomon, K.H. and Oliphant, J.C., 1996. Drop size distributions for irrigation sprinklers. Transactions of the ASAE, 39(3), 839-845.

Kjelgren, R., Rupp, L. and Kilgren, D., 2000. Water Conservation in Urban Landscapes. Hortscience, 35(6), 1037-1040.

Kohl, R. A. and DeBoer, D. W., 1984. Drop size distributions for a low pressure spray type agricultural sprinkler. Transactions of the ASAE, 27(6), 1836-1840.

Lamacq, S., 1997. Coordination entre l'offre et la demande en eau sur un périmètre irrigué : des scénarios, des systèmes, et des hommes... Unpublished Doctorate Thesis, CEMAGREF-ENGREF, 134p.

Lamaddalena, N. and Sagardoy, J. A., 2000. Performance analysis of on-demand pressurized irrigation systems. FAO irrigation and drainage paper, 59 (Food and A.). Rome.

Landau, S. and Everitt, B.S., 2004. A Handbook of Statistical Analyses using SPSS. Chapman & Hall/CRC Press LLC. ISBN 1-58488-369-3.

Lecina, S., Playán, E., Isidoro, D., Dechmi, F., Causapé, J. and Faci, J. M., 2005. Irrigation evaluation and simulation at the Irrigation District V of Bardenas (Spain). Agricultural Water Management, 73(3), 223-245.

Lecina, S., Isidoro, D., Playán, E. and Aragüés, R., 2010. Irrigation modernization and water conservation in Spain: The case of Riegos del Alto Aragón. Agricultural Water Management, 97, 1663-1675. Elsevier B.V.

Liyuan, X., Liping, C., Tianen, C., and Gao, Y. (in press). SOA-based precision irrigation decision support system. Mathematical and Computer Modelling. Elsevier Ltd.

Loh, M. T. Y. and Coghlan, P., 2003. Domestic Water Use Study in Perth, Western Australia. 1998-2001. Water Corporation. Australian Greenhouse Office, Perth, Wstern Australia, Australia. Retrieved from: http://www.watercorporation.com.au/_files/publicationsregister/12/Domestic_water_use_study.pdf.

Lorenzini, G., 2004. Simplified modelling of sprinkler droplet dynamics. Biosystems Engineering, 87(1): 1-11.

Lorite, I.J., Mateos, L. and Fereres, E., 2004. Evaluating irrigation performance in a Mediterranean environment - II. Variability among crops and farmers. Irrigation Science, 23 (2), 85-92.

Magarvey, R.H., 1956. Stain Method of drop size determination. Journal of Meteorology, 14: 182-184.

Malano, H. and Burton, M., 2001. Guidelines for benchmarking performance in the irrigation and drainage sector. FAO, Knowledge Synthesis Report.

Ministerio de Agricultura, Pesca y Alimentación, 2002. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de las explotaciones agrícolas de Aragón en 2001. Subsecretaría de agricultura, pesca y alimentación, Ministerio de Agricultura, Pesca y Alimentación (MAPA), Government of Spain.

Ministerio de Agricultura, Pesca y Alimentación, 2003. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de las explotaciones agrícolas de Aragón en 2002. Subsecretaría de agricultura, pesca y alimentación, Ministerio de Agricultura, Pesca y Alimentación (MAPA), Government of Spain.

Ministerio de Agricultura, Pesca y Alimentación, 2004. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de las explotaciones agrícolas de Aragón en 2003. Subsecretaría de agricultura, pesca y alimentación, Ministerio de Agricultura, Pesca y Alimentación (MAPA), Government of Spain.

Ministerio de Agricultura, Pesca y Alimentación, 2005. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de las explotaciones agrícolas de Aragón en 2004. Subsecretaría de agricultura, pesca y alimentación, Ministerio de Agricultura, Pesca y Alimentación (MAPA), Government of Spain.

Ministerio de Agricultura, Pesca y Alimentación, 2006. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de las explotaciones agrícolas de Aragón en 2005. Subsecretaría de agricultura, pesca y alimentación, Ministerio de Agricultura, Pesca y Alimentación (MAPA), Government of Spain.

Martínez-Cob, A. and García-Vera, M.A., 2004. Revisión de las Necesidades Hídricas Netas de los cultivos de la cuenca del Ebro. Internal Report 2004-PH-12.I. Confederación Hidrográfica del Ebro, Zaragoza.

Martínez-Cob, A., Playán, E., Cavero, J. and García-Vera, M.A., 2005. Recopilación de suministros en cultivos eficientes de la cuenca del Ebro y comparación con las dotaciones objetivo. Internal Report 2005-PH-21.I. Confederación Hidrográfica del Ebro, Zaragoza.

McCready, M.S., Dukes, M.D. and Miller, G.L., 2009. Water conservation potential of smart irrigation controllers on St. Augustinegrass. Agricultural Water Management, 96(11), 1623-1632.

Merot, A., Bergez, J.-E., Capillon, A., and Wery, J., 2008. Analysing farming practices to develop a numerical, operational model of farmers' decision-making processes: An irrigated hay cropping system in France. Agricultural Systems, 98, 108-118.

Merriam, J. L. and Keller, J., 1978. Farm irrigation system evaluation: a guide for management. Utah State University, Logan, Utah.

Ministerio de Medio Ambiente y Medio Rural y Marino, Gobierno de España, 2011. Estaciones Agroclimáticas. Red SIAR. (Agrometeorological stations. SIAR network) Retrieved from: http://www.mapa.es/siar/Informacion.asp.

Molden, D.J., 1997. Accounting for water use and productivity. SWIM Paper1. Colombo, Sri Lanka: International Water Management Institute.

Molden, D.J., Sakthivadivel, R., Perry, C.J., de Fraiture, C. and Kloezen, W.H., 1998. Indicators for comparing performance of irrigated agricultural systems. Research Report 20. Colombo, Sri Lanka: International Water Management Institute.

Montero, J., Tarjuelo, J.M. and Carrión, P., 2001. SIRIAS: a simulation model for sprinkler irrigation: II. Calibration and validation of the model. Irrigation Science, 2001(20), 85-98.

Montero, J., Tarjuelo, J.M. and Carrión, P., 2003. Sprinkler droplet size distribution measured with an optical spectropluviometer. Irrigation Science, 2003(22), 47-56.

Morari, F. and Giardini, L., 2001. Estimating evapotranspiration in the Padova Botanical Garden. Irrigation Science, 20, 127-137.

Moreno, T., Ibáñez, J.C. and Cubillo, F., 2007. Los usos finales del agua como base para la caracterización y predicción de la demanda en la Comunidad de Madrid. V Congreso

Nacional de la Ingeniería Civil. Desarrollo y Sostenibilidad en el marco de la ingeniería (Vol. 2001, p. 11). Sevilla, 26-28 Noviembre. Retrieved from: http://www.ciccp.es/biblio_digital/V_Congreso/congreso/pdf/010317.pdf.

Ortíz, J.N., Tarjuelo, J.M. and De Juan, J.A., 2009. Characterisation of evaporation and drift losses with centre pivots. Agricultural Water Management, 96(11), 1541-1546.

Parés-Franci, M., Saurı-Pujol, D. and Domene, E., 2006. Evaluating the Environmental Performance of Urban Parks in Mediterranean Cities : An Example from the Barcelona Metropolitan Region. Environmental Management, 38(5), 750-759.

Pastor, M. and Orgaz F., 1994. Riego deficitario del olivar. Agricultura, 746, 768-776.

Perry, C., 2007. Efficient irrigation; Inefficient communication; Flawed recommendations. Irrigation and Drainage, 56(4), 367-378.

Perry, C.J., 1999. The IWMI water resources paradigm - definitions and implications. Agricultural Water Management 40(1), 45-50.

Perry, C.J., 2001. Charging for irrigation water: The issues and options, with a case study from Iran. Research Report 52. Colombo, Sri Lanka: International Water Management Institute.

Pinilla, V., 2002. El desarrollo de la agricultura de regadío en la Cuenca del Ebro en el siglo XX. X Congreso de Historia Agraria, Sitges (Barcelona).

Playán E., Cavero J., Mantero I., Salvador R., Lecina S., Faci J.M., Andrés J., Salvador V., Cardeña G., Ramón S., Lacueva J.L., Tejero M., Ferri J. and Martínez-Cob A., 2007. A Database Program for Enhancing Irrigation District Management in the Ebro Valley (Spain). Agricultural Water Management, 87 (2): 209-216.

Playán, E. and Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agricultural Water Management, 80(1-3), 100-116.

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A. and Sánchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agricultural Water Management, 76(3), 139-159.

Playán, E., Zapata, N., Faci, J.M., Tolosa, D., Lacueva, J.L., Pelegrín, J., Salvador, R., Sánchez, I. and Lafita, A., 2006. Assessing sprinkler irrigation uniformity using a ballistic simulation model. Agricultural Water Management, 84(1-2), 89-100.

Quails, R. J., Scott, J. M. and DeOreo, W. B., 2001. Soil moisture sensors for urban landscape irrigation: Effectiveness and reliability. Journal of the American Water Resources Association. 37(3), 547-559.

Renzetti, S., 2002. The Economics of Water Demands. Kluwer Academic Press, Norwell, Massachusetts.

Rodrigues, G.C. and Pereira, L.S., 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosystems Engineering, 103(2009):536-551.

Salles, C., Poesen, J. and Borselli, L., 1999. Measurement of simulated drop size distribution with an optical spectro pluviometer: Sample size considerations. Earth Surface Processes and Landforms, 24(6), 545-556.

Sanchez, I., Zapata, N. and Faci, J.M., 2010. Combined effect of technical, meteorological and agronomical factors on solid-set sprinkler irrigation: I. Irrigation performance and soil water recharge in alfalfa and maize. Agricultural Water Management, 97(10), 1571-1581.

Seginer, I., Nir, D. and von Bernuth, D., 1991. Simulation of wind-distorted sprinkler patterns. Journal of Irrigation and Drainage Engineering, ASCE, 117(2), 285-306.

Sisquella M., Lloveras J., Álvaro J., Santiveri P. and Cantero C., 2004. Técnicas de cultivo para la producción de maíz, trigo y alfalfa en regadíos del valle del Ebro. Universitat de Lleida, Lleida, Spain, 105 pp.

St. Hilaire, R., Arnold, M., Wilkerson, D.C., Devitt, D.A., Hurd, B.H., Lesikar, B.J., Lohr , V. I., Martin, C. A., McDonald, G. V., Morris, R. L., Pittenger, D. R., Shaw, D. A., Zoldoske, D.F., 200). Efficient Water Use in Residential Urban Landscapes. Hortscience, 43(7), 2081-2092.

Statistical package for social sciences (SPSS-IBM) v.19, 2010.

Styczen, M., Poulsen, R.N., Falk, a K. and Jørgensen, G.H., 2010. Management model for decision support when applying low quality water in irrigation. Agricultural Water Management, 98(3), 472-481. Elsevier B.V.

Sudheer, K.P. and Panda, R.K., 2000. Digital image processing for determining drop sizes from irrigation spray nozzles. Agricultural Water Management, 45(2000), 159-167.

Syme, G.J., Shao, Q., Po, M. and Campbell, E., 2004. Predicting and understanding home garden water use. Landscape and Urban Planning, 68, 121-128.

Tarjuelo, J.M., Montero, J., Honrubia, F.T., Ortiz, J.J. and Ortega, J.F., 1999. Analysis of uniformity of sprinkle irrigation in a semi-arid area. Agricultural Water Management, 40(2-3), 315-331.

Tarjuelo, J.M., Ortega, J.F., Montero, J. and De Juan, J.A., 2000. Modelling evaporation and drift losses in irrigation with medium size impact sprinklers under semi-arid conditions. Agricultural Water Management, 43(2000), 263-284.

Thompson, A.L., Gilley, J.R. and Norman, J.M., 1986. Simulation of sprinkler water droplet evaporation above a plant canopy. Paper - American Society of Agricultural Engineers.

Thornthwaite C.W., 1931. The Climates of North America: According to a New Classification. Geographical Review, Vol. 21 (4), 633-655.

Thornthwaite C.W., 1948. An Approach toward a Rational Classification of Climate. Geographical Review, Vol. 38 (1), 55-94.

Trimer, W.L., 1987. Sprinkler evaporation loss equation. Journal of Irrigation and Drainage Engineering, ASCE 113(4): 616-620.

Vickers, A., 2001. Handbook of Water Use and Conservation: Homes, Landscapes, Business, Industries, Farms. Waterplow Press, Amherst, Massachusetts. ISBN 10: 1-931579-07-5

Von Bernuth, R.D. and Gilley, J.R., 1984. Sprinkler droplet size distribution estimation from single leg test data. Transactions of the ASAE, 27(5), 1435-1441.

Ward, F.A. and Pulido-Velázquez, M., 2008. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences of the United States of America, Vol. 105(47), 18215-18220.

White, R., Havalak, R., Nations, J., Pannkuk, T., Thomas, J., Chalmers, D. and Dewey, D., 2004. How Much Water is Enough? Using PET to Develop Water Budgets for Residential landscapes. Texas Water Resources Institute. College Station, Texas, USA. Retrieved from: http://repository.tamu.edu/bitstream/handle/1969.1/6100/tr271.pdf?sequence=1.

Wiesner, J., 1895. Beiträge zur Kentniss der Grösze des tropischen Regens. Akademie der Wissenschaften, Mathematika-Naturwissenschaften Klasse, vol. 104, Sitz Berlin Verlag, pp. 1397–1434.

Wriedt, G., Van Der Velde, M., Aloe, A. and Bouraoui, F., 2008. A European irrigation map for spatially distributed agricultural modelling. Agricultural Water Management. 96 (5), 771-789

Zapata, N., Playán, E., Skhiri, A. and Burguete, J., 2009. Simulation of a collective solid-set sprinkler irrigation controller for optimum water productivity. Journal of Irrigation and Drainage Engineering, 135 (1), 13-24.

Zapata, N., Playán, E, Martinez-Cob, A., Sánchez, I., Faci, J.M. and Lecina, S., 2007. From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agricultural Water Management, 87, 187-199

Zapata, N., Playán, E., Skhiri, A. and Burguete, J., 2009. Simulation of a collective solid-set sprinkler irrigation controller for optimum water productivity. Journal of Irrigation and Drainage Engineering, 135(1), 13-24.

8. ÍNDICES DE FIGURAS Y TABLAS

ÍNDICE DE FIGURAS

ÍNDICE DE TABLAS